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Responsible Innovation Definitions, Practices, and Motivations from Nanotechnology Researchers in Food and Agriculture

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Abstract The growth of responsible innovation (RI) scholarship has been mirrored by a proliferation of RI definitions and practices, as well as a recognition of the importance of context for RI. This study investigates how researchers in the field of nanotechnology for food and agriculture (nano-agrifoods) define and practice RI, as well as what motivations they see for pursuing RI. We conducted 20 semi-structured interviews with nano-agrifood researchers from industry and academia in the USA, where we asked them to describe their RI definitions, practices, and motivations. We analyzed the emergent themes from these interviews, including how the themes aligned with four prominent RI principles (anticipation, inclusion, reflexivity, responsiveness). We found that nano-agrifood researchers largely focused their descriptions of RI definitions, practices, and motivations around a narrow envisioning of the RI principle of anticipation — emphasizing product safety, efficacy, and efficiency. We also found noteworthy tensions surrounding the less frequently mentioned RI principles. For example, some researchers envisioned inclusion as a way to align products with industry interests while others saw it as a way to align products with the public good. Concerning motivations for RI, some researchers viewed RI as a way to protect one's reputation and avoid lawsuits while others viewed it as a way to improve human well-being and solve societal problems. Given these findings, future efforts to foster RI within nano-agrifoods should promote discussions among researchers concerning what it means to responsibly innovate and what practices this could entail, particularly beyond ensuring product safety, efficacy, and efficiency.

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Introduction

Responsible innovation (RI) is a governance paradigm for emerging technologies and innovation more broadly that builds upon anticipatory governance [1], upstream engagement [2], and theories of technology assessment such as constructive technology assessment [3] and real-time technology assessment [4]. As the literature on RI continues to grow and mature, a diversity of

RI definitions, practices, and motivations have emerged [5–9]. We begin this article by first demonstrating how RI definitions, practices, and motivations are not concretely defined nor universally agreed upon. In the face of this divergence of definitions, practices, and motivations, we review the importance of context when envisioning and pursuing RI. We then introduce our study on what form RI definitions, practices, and motivations take specifically among researchers in academia and industry working on nanotechnology in food and agriculture (nano-agrifoods).

Definitions of RI: While succinct definitions of RI exist, like the often cited "taking care of the future through collective stewardship of science and innovation in the present" [10], a key component of RI definitions are tenants or key principles. Most prominently, Stilgoe et al. [10] propose four key principles of RI: anticipation, inclusion, reflexivity, and responsiveness. Others suggest alternative principles to include within the definition of RI such as transparency/openness, sustainability, and care [5, 6, 11]. In addition, some scholars have defined RI through attributes to be realized in the products of innovation like social desirability, ethical responsibility, high scientific quality, and market competitiveness [6]. The diversity of reported dimensions of RI is further complicated by their independent meaning and conceptualization. For example, one review of the RI literature found eleven ways of providing specific meaning to the RI principle of "inclusion," including diversify values, diversify expertise, democratize R&D decisions, earn public support for potential outcomes, define desirable outcomes, identify and clarify social-ethical impacts, diversify alternatives, assess social desirability, expand capacity for change, contribute to social desirability of outcome, and contribute to scientific quality of outcome [6].

RI definitions can also be differentiated from the "Responsible Research and Innovation" (RRI) paradigm. While RI and RRI are sometimes conflated, they have different roots and key components. RI's beginnings are more aligned with academia, while RRI emerged from a public policy and institutional context — namely the European Commission [11]. RRI emphasizes the principles of public engagement, open access/science, gender, science education, and ethics [11]. Our study focuses primarily on RI but acknowledges that the developments of RRI have influenced discourse in this area more broadly.

Practices of RI: In addition to the breadth of definitions and principles, there are also a host of action-oriented practices or approaches for achieving RI. For example,

Lubberink et al. [12] identify four main approaches to achieve the RI principle of inclusion, specifically in the context of industry: (i) consult, integrate, or collaborate with key stakeholder groups (e.g., the public, supply-chain actors, end-users, non-governmental organizations, experts, and governmental agencies); (ii) user-innovation through crowdsourcing, focus groups, or bottom-up innovation; (iii) community visits; and (iv) public platforms for expressing needs and concerns. Stilgoe et al. [10] identify nine main practices to pursue "inclusion," focused more on methods: (i) consensus conferences, (ii) citizens' juries and panels, (iii) focus groups, (iv) science shops, (v) deliberative mapping, (vi) deliberative polling, (vii) lay membership of expert bodies, (viii) user-centered design, and (ix) open innovation. Similar to the RI principle of inclusion, various other practices exist for other RI principles such as anticipation (e.g., conducting safety studies to evaluate if a substance of new material may cause health or environmental impacts), reflection (e.g., codes of conduct), and responsiveness (e.g., adding food labels in response to consumer desired transparent information on what is in the food supply).

Motivations for RI: A wide range of potential motivations exist for pursuing RI. Von Schomberg and Hankins [13] offer motivations for pursuing RI that include indictments of existing innovation systems:(i) moving from an exclusive focus on risk and safety issues in the governance of new technology to considering societal desirability; (ii) moving away from the idea that economic markets can alone achieve societally desirable innovations; (iii) moving from assuming innovation is an inherent good to steering innovation towards socially beneficial objectives; and (iv) moving from maximizing technological potential to aligning innovation with broadly shared public values and expectations. RI motivations may also be more applied and influenced by institutional context (e.g., industry, government, or academia) [12, 14–18]. For example, some innovators may pursue RI because it aligns with their desire to benefit the public good, while others may pursue RI to help achieve product success or avoid liability, outside of an explicit commitment to the broader public good.

This brief description demonstrates the breadth of RI definitions, practices, and motivations and emphasizes the need for increased attention to how RI is defined and practiced in particular contexts [17, 19, 20]. Noting that RI takes different forms in different contexts suggests it is more fluid than a prescriptive set of definitions and practices. Even so, there is still a need to match an

attentiveness to context with an awareness of what RI principles are being emphasized and left out of how RI is defined and practiced [17]. As a foundation, the four key principles articulated by the most cited article on RI [10] imply that a critical eye should be brought towards RI definitions and practices that do not (i) consider the future impacts and implications of innovation (anticipation), (ii) open questions and decisions concerning innovation to inclusive dialogue (inclusion), (iii) hold a mirror up to one's motivations and assumptions (reflexivity), and (iv) change the direction of innovation based on stakeholder and public values and RI activities (responsiveness).

RI of Nano-agrifoods: RI has often been called for with emerging technologies such as synthetic biology, geoengineering, and nanotechnology because of the high degrees of uncertainty, complexity, and controversy associated with these technologies [16, 21]. In the context of nanotechnology, a variety of RI definitions, practices, and motivations have been discussed. Some studies report that RI practices have occurred at the end of product design and innovation stages rather than in earlier stages of the innovation cycle [22], and that most nano-innovation has occurred according to "business as usual" strategies rather than whole-hearted adoption of RI in practice [23]. Others have noted barriers to putting RI theory into practice for fields of nanotechnology, including the lack of concrete guidelines for RI as well as the lack of institutionalization of principles and practices of responsible nano-innovation, leading to "interesting side projects" rather than meaningful and robust incorporation of RI practices within nano-innovation cycles [24]. This stands in contrast to practices suggested in the literature [e.g., 10, 25] that incorporate inclusive and reflexive deliberation to not only ensure safe and ethical innovation but also to reflect on the purposes and motivations driving innovation. Some companies may also be motivated to pursue RI as a way to ensure the "responsible handling of nanomaterials" and to provide a "commitment to current employees, customers, suppliers, and society," as in the case of BASF's Nanotechnology Code of Conduct [24].

While there have been other studies reporting on how RI has been applied to nanotechnology as a whole [e.g., 24, 26–28], there has not been work exploring what form RI takes for nano-agrifoods specifically. Given the importance of context for understanding RI, we were particularly interested in understanding how RI is being defined and practiced by researchers working in nano-agrifood sectors, and what factors motivate their pursuit of RI. There is a wide range of nano-enabled applications on the market or in development in food and agriculture sectors (e.g., nano-fertilizers, nano-pesticides, nano-encapsulation, nano-emulsions, nano-scale food additives). These nano-agri-food applications are often touted for their potential ability to provide improved nutritional value of process foods, longer shelf lives of fresh cut produce, and most sustainable alternatives to conventional agrochemicals [29, 30].

To explore how RI is being envisioned and practiced by nano-agrifood researchers, we conducted in-depth, semi-structured interviews with 20 researchers in industry and academia based in the United States (U.S.) working on a range of nano-agrifood applications. After outlining our methods, we begin our findings section by presenting a summary from each key area of the interview: How do nano-agrifood researchers define RI? How do they define non-RI? What practices do they use to achieve RI? What motivations do nano-agrifood researchers see for pursuing RI? We then present findings on how the RI definitions, practices, and motivations articulated by nano-agrifood researchers relate to the four key principles of RI (i.e., anticipation, inclusion, reflexivity, and responsiveness). These results help better understand exactly how nanotechnology researchers are defining and practicing RI within food and agriculture sectors, as well as what aspects of RI they are emphasizing and (knowingly or unknowingly) sidelining. This study also sheds light on how well academic definitions of RI are spreading to researchers — vital information to help inform efforts to achieve a robust and balanced approach to RI for nano-agrifoods and other emerging technologies within food and agriculture.

Methods

To study how nano-agrifood researchers define and practice RI within nano-agrifood sectors, we conducted 20 individual, in-depth, semi-structured interviews. To identify our pool of potential participants, we chose the selection criteria of (1) individuals from U.S. industry and academia that were (2) involved with research on nanotechnology applications within food and agriculture sectors, including food production, food processing, agriculture production, agrochemical production or use, and veterinary medicine. We searched for potential participants that matched these selection criteria within peer-reviewed literature, non-peer-reviewed reports,

conference attendee lists, the U.S. Department of Agriculture Current Research Information System database, and publicly accessible company websites. In total, we identified 45 potential participants from industry and 50 from academic institutions using these search criteria.

We invited potential participants to take part in the study using email invitations. Twenty individuals, including eight from U.S.-based industry and twelve from U.S. academic institutions agreed to take part in the study. Of the participants from industry, two came from large companies that employed over 5000 employees and the rest came from small companies with fewer than 100 employees. Two of the participants' companies employed less than five people. A majority of industry participants held PhDs. Positions held by industry participants from small companies included CEO and President, while the positions of participants from medium or large companies included Vice-President of Research and Vice-President Product Development. Of the participants from academia, they all held PhDs and were affiliated with a U.S.-based university, with the vast majority holding professorships. Our industry and academia interviewees worked in a range of nano-agrifood research areas including nano-pesticides, nano-fertilizers, nano-food processing, nano-dietary supplements, and nano-veterinary medicine. Some interviewees described being involved in more than one research area.

We received Institutional Review Board approval via NC State University for this study (Protocol 19207), and all participants provided written consent before participating in the interviews. We conducted the interviews using a web-meeting platform between December 2019 and June 2020. Interviews generally lasted between 60 and 75 min. The interview protocol consisted of eleven semi-structured questions exploring how researchers define and practice RI. We sent the interview questions to participants in advance of the interview. The first interview question had interviewees describe their area of expertise, current position, and nanotechnology research. After that introductory question, we asked the following four questions that we address in this article:

1. From your own point of view, what does it mean to innovate responsibly?
2. What does it mean to *not* innovate responsibly?
3. What formal or informal practices do you use to innovate responsibly with nanotechnology for food and agriculture?
4. What motivations exist for pursuing nanotechnology responsible innovation?

Interviewees were not provided a definition of "responsible innovation" or how to "innovate responsibly" since we wanted to understand their own views on RI and how they compared to the academic literature. While interviewees could have researched RI between receiving our questions and when the interviews were conducted, none of the interviewees mentioned doing so and none of their answers directly quoted from the RI literature. Notes were taken during the interview to ensure comprehension and to inform follow-up questions. All interviews were audio-recorded and transcribed, and de-identified transcriptions were qualitatively analyzed using the software program Dedoose.

The goal of the initial data analysis was to examine how interviewees articulated RI definitions, practices, and motivations, and to understand how widely shared these definitions, practices, and motivations were across interviewees. Using Dedoose, we coded the transcripts using descriptive coding and subcoding [31]. In this process, we first read through the transcript of each interview and assigned parent codes to each excerpt of an interview that related to one of the key topics of our inquiry (i.e., RI definitions, practices, motivations). For each excerpt related to a parent code, we then created a child code to capture exactly how the interviewee articulated each topic. Second, once we had created the initial set of child codes for each parent code, we revisited each child codes to ensure the consistency within each code — combining codes and creating new codes as needed. This final list of child codes represents the emergent themes for each key topic of our study. We also identified the number of interviews each theme was mentioned in. Finally, we identified key quotations that captured each theme to present in the results. One researcher conducted the coding, another team member reviewed the coding scheme for reliability, and all emerging findings were reviewed for consistency during research team meetings.

We also analyzed across topics and themes to investigate what principles of RI were present and absent in researcher RI definitions, practices, and motivations. Specifically, we asked: what form did anticipation, inclusion, reflexivity, and responsiveness take in researcher RI definitions, practices, and motivations? We looked at each emergent theme and its associated quotations to examine whether it related to anticipation, inclusion, reflexivity, and/or responsiveness as defined by Stilgoe et al. [10]. The goal was to understand how narrowly or broadly nanotechnology researchers were envisioning RI. If, for example,

all RI definitions, practices, and motivations only included one key RI principle, then that would indicate a narrow envisioning of RI relative to the academic literature.

Findings

Below we describe our findings according to the key study questions of: How do nano-agrifood researchers define RI? How do they define non-RI? What practices do they use to achieve RI? What motivations do they see for pursuing RI? And finally, how do the RI definitions, practices, and motivations articulated by nano-agrifood researchers relate to four key RI principles of anticipation, inclusion, reflexivity, and responsiveness?

Definitions of Responsible Innovation

Our analysis of researcher responses to the question "What does it mean to innovate responsibly?" yielded six emergent themes: (1) *Products do not harm human health and/or the environment*, (2) *Create effective and efficient products*, (3) *Use systems thinking, life cycle analysis or sustainable practices*, (4) *Adhere to regulations*, (5) *Develop products that are publicly acceptable*, and (6) *Engage stakeholders* (Table 1). Of these six themes, the two most frequently mentioned themes involved product safety, efficacy, and efficiency: (1)

Products do not harm human health and/or the environment (100% of study participants, i.e., 20/20 participants) and (2) *Create effective and/or efficient products* (80% of participants). For example, one respondent echoed these themes in response to this question: "Responsible commercialization is understanding that the products are safe and effective and you are a good steward of the environment."

Two less frequently mentioned themes highlighted specific processes to achieve safe products: *Use systems thinking, life cycle analysis, or sustainable practices*, and *Adhere to regulations*. Another infrequently mentioned theme, *Engage stakeholders*, emphasized the importance of considering a breadth of perspectives within innovation. Key to this definition of RI was not being solely motivated by a single company's profits, and engaging stakeholders was seen as a way to accomplish that. As one industry researcher said, "You can tell when there's responsible innovation, when there's comfortable stakeholders, and sort of the more diverse the stakeholders the better…. When you collect those individuals or different entities and organizations, you start having to apply some of that public good, right? Because once you bring in diverse stakeholders together, you're no longer motivated for one sector or one company's profits."

Table 1 Interviewee themes and exemplary quotes that emerged from the interview question: "What does it mean to innovate responsibly?" % = percentage of interview participants, out of 20 total, who mentioned the theme. [A] indicates the quote is from an academic researcher, and [I] indicates the quote is from an industry researcher

Themes - Definition of responsible innovation	%	Sample excerpts
Products do not harm human health and/or the environment	100	"Just thinking about pros and cons of nanopesticides, where would they go, how will they affect the health of the consumer, the environment?" [A]
Create effective and/or efficient products	80	"Responsible commercialization is understanding that the products are safe and effective and you're a good steward of the environment." [I]
Use systems thinking, life cycle analysis, or sustainable practices	55	"Well, to do your very best to look over the horizon and see what the possible implications might be of a new technology and to consider their entire life cycle impacts." [A]
Adhere to regulations	15	"You also need to be aware of being compliant with the regulatory pathways, of course. I mean, you know, you have to be following the rules." [I]
Develop products that are publicly acceptable	15	"When I am defining a new product or thinking about a new research project, the first thing that comes into my mind is always about feasibility and also the acceptability of the final products. We have to make sure that we encapsulate a specific compound that is publicly acceptable." [A]
Engage stakeholders	10	"You can tell when there's responsible innovation, when there's comfortable stakeholders, and sort of the more diverse the stakeholders the better…. When you collect those individuals or different entities and organizations, you start having to apply some of that public good, right? Because once you bring in diverse stakeholders together, you're no longer motivated for one sector or one company's profits." [I]

Definitions of Non-responsible Innovation

To further explore nano-agrifood researcher perspectives on the definition of RI, we also asked interviewees what they thought it meant to *not* innovate responsibly (Table 2). In this case, we found that there was less agreement across participant responses compared to the previous question (Table 1). The two most frequently mentioned themes focused on product safety: (1) *Ignore non-target environmental and/or human impacts of products* (60% of participants) and (2) *Use hazardous, unknown, and/or uncontrollable substances in products* (35%). The most prevalent theme was captured by one academic researcher who described that to *not* innovate responsibly meant: "To purposely produce something that has an impact or an off-target impact and just ignore that. Not paying attention to the off-target impact."

Three of the less frequently mentioned themes (i.e., *Focus solely on profits*, *Avoid regulatory scrutiny*, and *Lack collaboration and interdisciplinarity*) described actions that could get in the way of achieving a safe product (Table 2). For example, researchers alluded to the idea that safe, and in their eyes therefore responsible, innovation could not be achieved by focusing solely on profits and ignoring potential environmental and human health impacts of a product. Alternatively, some noted that if you lack collaboration and interdisciplinarity, there are limitations to understanding the complex issues surrounding nano-agrifood products. For example, one academic researcher said, you need "partners who have skills in a wide range of subjects, including soil microbiologists, toxicologists, mechanical engineers, chemists, modelers"; otherwise, you may not really understand a product. Another theme, *Misleading by underselling or overselling*, concerned how people relate to nanotechnology and emphasized that considering "all nanotechnology" to be either good or bad oversimplifies the technology and neglects the importance of context in making such judgments.

Table 2 Interviewee themes and exemplary quotes that emerged from the interview question: "What does it mean to <u>not</u> innovate responsibly?" % = percentage of interview participants, out of 20 total, who mentioned the theme. [A] indicates the quote is from an academic researcher and [I] indicates the quote is from an industry researcher

Themes - Not innovating responsibly	%	Sample excerpts
Ignore non-target environmental and/or human health impacts of products	60	"To purposely produce something that has an impact or an off target impact and just ignore that. Not paying attention to the off target impact." [A]
Use hazardous, unknown and/or uncontrollable substances in products	35	"During the technology development, we have to make sure we don't use non-food materials. We don't want to use toxic compounds." [I]
Focus solely on profits	20	"Personally, that to me is putting profits over the safety and the efficacy and the responsibility for the end users and the people involved." [I]
Avoid regulatory scrutiny	20	"You wouldn't even tell the EPA [U.S. Environmental Protection Agency], 'hey, we have these nanoparticles in them', – you would try to hide that so that you could get the product out and just ignore the potential consequences." [I]
Mislead by underselling or overselling technology & safety	20	"If we rush to judgment and say nano is bad - blanket statement - that's wrong... It is so diverse that you cannot make that statement, nor can you make a statement that nano is safe for the same reason." [A]
Create inefficient or ineffective products	15	"Focusing solely on function, trying to obtain increased yield using a nonrenewable finite resource that is critical to whatever the technology would be. So there would be cost implications for that down the road, there would be availability implications which would be intertwined with economic considerations." [A]
Lack collaboration and interdisciplinarity	10	"You have to… learn the risk involved, and as long as you work with partners who have skills in a wide range of subjects, including soil microbiologists, toxicologists, mechanical engineers, chemists, modelers, then, you will have a better handle of this, and you're able to understand what would innovate responsibly mean. Otherwise, you might be just in a testing phase of materials, and you don't really understand." [A]

Practices of Responsible Innovation

Our analysis of researcher practices for achieving RI of nano-agrifoods yielded eight emergent themes. Similar to the definitions of RI, the three most frequently mentioned themes were dominated by concerns about safety: (1) *Consider, or conduct studies on, environmental and human health safety* (100% of study participants); (2) *Adhere to lab safety practices* (60%); and (3) *Use materials that are low risk* (55%) (Table 3). In reality, the first category, because of its broad framing, includes both the following categories on lab safety and using low-risk materials. We specifically include the categories *Adhere to lab safety practices* and *Use materials that are low risk* on their own because they were frequently mentioned in their own right.

The next two most frequently mentioned practices (i.e., *Engage stakeholders* and *Collaborate interdisciplinarily*) both highlight the importance of collaboration, but in different ways (Table 3). First, interviewees mentioned the importance of collaboration when discussing how a single discipline cannot adequately study nano-enabled agrifood applications because of their complexity. As one academic interviewee said, "You can't rely on yourself alone… We worked with a diverse body of experts, so we had toxicologists, we have life-cycle practitioners." This version of collaboration across disciplines was specific to concerns about achieving product safety, efficacy, and efficiency. A different end of collaboration, not directly associated with product safety, was articulated with the theme *Engage stakeholders*. This practice included collaborating with and receiving feedback from stakeholders and was associated with how researchers determined what specific products to pursue. In other words, in addition to safety, efficacy, and efficiency, what other considerations

Table 3 Interviewee themes and exemplary quotes that emerged from the interview questions "What formal or informal practices do you use to innovate responsibly with nanotechnology for food and agriculture?" % = percentage of interview participants, out of 20 total, who mentioned the theme. [A] indicates the quote is from an academic researcher and [I] indicates the quote is from an industry researcher

Themes - Responsible innovation practices	%	Sample excerpts
Consider, or conduct studies on, product environmental and human health safety	100	"We - not just me - all of my colleagues and collaborators, we understand very well that because we're working with materials that have smaller particle size, everything from worker safety to environmental safety to product effectiveness, they all have to go in tandem." [A]
Adhere to lab safety practices	60	"We follow all of the general normal safety procedures when we handle the nanoparticles; we treat them as any other biological agents as far as using PPE [personal protective equipment]." [A]
Use low risk materials in products	55	"My lab already knows we're only working with … [a certain type of] nanoparticles and not venturing out of this area. I found it very broad still. We can innovate a lot but at least I feel like it's a safe area to work with when it comes to risk." [A]
Engage stakeholders	45	"We're trying to avoid some kind of technology that they [the company] don't like... So, we always try to learn their views… then we take those back to the lab to see how our research, our technology can be developed to meet those expectations from them." [A]
Collaborate interdisciplinarily	30	You can't rely on yourself alone... because if you work on something on yourself, you really cannot disclose the full picture of the product, or the material... We worked with a diverse body of experts, so we had toxicologists, we have life-cycle practitioners." [A]
Adhere to regulations	20	"The first question is, you know, what are the regulatory compliance pathways... what studies do we need to do to convince first ourselves, then the regulators that this can get a green light and doesn't have problems." [I]
Hold lab meetings to discuss research	20	"They all have this overarching theme or this underlying sustainability, or really the green chemistry principles that guide the work that they do. And so, you know, in group meetings when they all take turns presenting their work... my hope is that these messages and the broader applicability of how you innovate responsibly, or how you would apply these principles in different contexts comes through." [A]
Conduct literature reviews	20	"Then as a scientist you do a really good job in literature review… understand the toxicological profile, understand how the plant is going to respond, understand, are they going to be degraded? If they're not degraded what happens over time?" [A]

should inform what paths nano-agrifoods innovation take? For example, academic researchers discussed the importance of reaching out to industry or product users to determine if potential research trajectories were promising. As one academic interviewee said: "We're trying to avoid some kind of technology that they [the company] don't like… So, we always try to learn their views… then we take those back to the lab to see how our research, our technology, can be developed to meet those expectations from them." As discussed in our section "Key RI Principles Across Researcher RI Definitions, Practices, and Motivations," however, the desire to align innovation with the interests of industry was not the only end that researchers articulated, as they also mentioned aligning innovation with the pursuit of public goods that benefit society.

Safety, efficacy, and efficiency were once again key factors in the three least frequently mentioned themes (i.e., *Adhere to regulations*; *Hold lab meetings to discuss research*; and *Conduct literature reviews*) (Table 3). These themes represent practices that interviewees found important for ensuring that proper research was conducted to help support product safety and effectiveness.

Motivations for Pursuing Responsible Innovation

Our analysis of the question "What motivations exist for pursuing nanotechnology responsible innovation?" yielded eight emergent themes, each representing a reason why researchers pursue RI for nano-agrifoods. Similar to the previously described themes, the most prevalent motivations involved safety, effectiveness, and efficiency: *Not harm human health and/or the environment* (80%) and *Create more efficient and effective products* (60%). The prevalence of these two themes reinforces how central environmental and human health safety as well as efficiency and efficacy were to researcher notions of RI. The third most prevalent theme, however, was the motivation to *Improve human well-being and/or solve societal problems*. This broadened the focus beyond safe, effective, and efficient products to the purpose of innovation itself. One industry researcher articulated the desire to solve societal problems in the following way: "It's exciting to see somebody who has had a problem, has not been able to solve

it, and I can help them solve that problem, and I can help them rescue a crop, or rescue a yield, or just frankly use less fertilizer."

Because of the topic area of our study, many of the societal problems that researchers articulated had to do with the environmental and human health impacts of intensive agriculture. The solutions they discussed involved using nanotechnologies and/or engineered nanomaterials to create agrifood products that were more efficient, effective, and safe than conventional counterparts. The emphasis on solving societal problems as the motivation for RI stands in contrast to three other motivations articulated by researchers that align with industry interests: (1) *Protect reputation*, (2) *Avoid liability*, and (3) *Better understand and market your product*. The emphasis on safety and efficacy highlighted across our findings was also embedded in participant comments on these three themes — participants linked protecting their reputations and liability with demonstrating adequate product safety and efficacy (see Table 4). Researchers also articulated the RI motivation of *Better understand and market your product* in terms of safety and efficacy, as described by one industry researcher: "To really understand your product and its points of differentiation against the competition you do a lot of research that's not in that regulatory framework context. And so, understanding your competitive advantage a lot of times will include this product is more effective and/ or safer, and/or better in these ways." This researcher, then, sees RI as aligning with the need to conduct research beyond what is required by regulations and recognizes how this can support finding one's competitive advantage.

Finally, two of the other motivations that researchers mentioned — *Responsible innovation aligns with the mission of academic discipline* and *Research integrity and ethics* — show that some researchers view RI as aligning with the general norms of producing high quality research and products of innovation. For example, one academic researcher discussed the motivations for pursuing responsible nano-innovation in the context of their environmental engineering academic discipline: "The key motivation if you're an environmental engineer is that you don't want to do any harm. You want to make sure that sustainability is at the forefront of all discovery and

you want to avoid the unintended consequences from a change from the status quo." This researcher sees both the environmental engineering discipline and RI as being about innovation that is sustainable and that avoids unintended consequences. Another academic researcher described their motivation for RI in terms of general research integrity and ethics: "We know, as a scientist, that research integrity, ethics, that's a foundation."

Key RI Principles Across Researcher RI Definitions, Practices, and Motivations

In our analysis, we also looked across the emergent themes from nano-agrifood researcher RI definitions,

practices, and motivations to examine whether and how four key RI principles (i.e., anticipation, inclusion, reflexivity, and responsiveness) were present. Here we describe how each RI principle emerged across researcher RI definitions, practices, and motivations.

Anticipation. Anticipation — simply defined as considering the future impacts and implications of innovation [25] — was an essential component of researcher discussions of RI definitions, practices, and motivations, although it was primarily envisioned through the lens of product safety, efficacy, and efficiency. In reviewing the themes relating to anticipation, we found that they all concerned product safety, efficacy, and efficiency (Table 5). Table 5 also shows

Table 4 Interviewee themes and exemplary quotes that emerged from the interview questions "What motivations exist for pursuing nanotechnology responsible innovation?" % = percentage of interview participants, out of 20 total, who mentioned the theme. [A] indicates the quote is from an academic researcher and [I] indicates the quote is from an industry researcher

Themes - Responsible innovation motivations	%	Sample excerpts
Not harm human health and/or the environment with products	80	"I think, food safety and in agriculture, food safety is our most, our highest priority. We're responsible for feeding people that could get sick if we chose the wrong product." [A]
Create more efficient and effective products	60	"We want to improve the efficacy of the pesticides, but we do not want to damage the environment while we're at it." [A]
Improve human well-being and/or solve societal problems	55	"It's exciting to see somebody who has had a problem, has not been able to solve it, and I can help them solve that problem, and I can help them rescue a crop, or rescue a yield, or just frankly use less fertilizer, which is the one I get the most excited about." [I]
Responsible innovation aligns with mission of academic discipline	35	"The key motivation if you're an environmental engineer is that you don't want to do any harm. You want to make sure that sustainability is at the forefront of all discovery and you want to avoid the unintended consequences from a change from the status quo. The thing is, we know the status quo is so bad in terms of the environmental impacts of agriculture that we have to do something." [A]
Protect reputation	25	"Simply put, because the company and the investors plan to be in this game for the long term, it's about covering your butt. If we're going to be in it 20 years, we can't find out in 10 years… something that affects our reputation or affects our growers or the environment they're growing in." [I]
Avoid liability	20	"I think the motivation is obviously you don't want to get sued, right... Once the farmer puts stuff on his field, that's it. If something goes wrong, then he could go back to say what the heck, you said you would do this, but it actually killed everything, right, so you don't want that to happen, so that's one major driver." [I]
Better understand and market your product	15	"To really understand your product and its points of differentiation against the competition you do a lot of research that's not in that regulatory framework context. And so, understanding your competitive advantage a lot of times will include this product is more effective and/or safer, and/or better in these ways." [I]
Research integrity and ethics	15	"Well, we know, as a scientist, that research integrity, ethics, that's a foundation." [A]

that the number of themes relating to anticipation (and in this instance, product safety, efficacy, and efficiency) far outnumbered those having to do with other key principles of RI. Furthermore, as shown within Table 1-4, the most frequently mentioned themes by researchers all had to do with safety, efficacy, and efficiency. While the presence of product safety, efficacy, and efficiency is not surprising, the fact that it so overpowered other considerations is noteworthy. Safety, efficacy, and efficiency represent only part of anticipation (e.g., it can also include considering political, social, and economic implications of a technology), and moving past a sole focus on safety, efficacy, and efficiency in innovation governance was one of the justifications for the development of RI in the first place [13].

Inclusion. Inclusion — opening questions and decisions concerning innovation to inclusive dialogue [25] — was much less frequently mentioned across researcher RI definitions, practices, and motivations. It was present, however, in the context of the themes: *Collaborate interdisciplinarily* and *Engage stakeholders*. First, the inclusion of a diversity of types of expertise was seen as a necessary means to achieve safe, effective, and efficient products (see *Collaborate interdisciplinarily* in Table 3). The complexity of nanotechnologies and the systems in which they are used required an interdisciplinary approach to, as one academic researcher put it, "disclose the full picture of the product." The second form of inclusion involved the reoccurring theme of *Engage stakeholders*. Within

Table 5 How emergent themes from nano-agrifood researcher RI definitions, practices, and motivations relate to four key RI principles (i.e., anticipation, inclusions, reflexivity, and responsiveness). Note, in the table "w.r.t." = with regard to

Interview topics	Interview themes related to each RI principle			
	Anticipation	*Inclusion*	*Reflexivity*	*Responsiveness*
Definitions of RI	• Products do not harm human health and/or the environment • Create effective and efficient products • Use systems thinking, life cycle analysis or sustainable practices • Adhere to regulations	• Engage stakeholders	• Engage stakeholders	• Develop products that are publicly acceptable
Definitions of NOT RI	• Ignore non-target environmental and/or human health impacts • Use hazardous unknown and/or uncontrollable substances • Avoid regulatory scrutiny • Create ineffective or inefficient products • Lack collaboration and interdisciplinarity • Focus solely on profits • Mislead by underselling or overselling technology and safety	• Lack collaboration and interdisciplinarity		
RI practices	• Consider, or conduct studies on, environmental and human health safety • Adhere to lab safety practices • Use low risk materials in products • Collaborate interdisciplinarily • Adhere to regulations • Hold lab meetings • Conduct literature reviews	• Engage stakeholders • Collaborate interdisciplinarily	• Engage stakeholders • Collaborate interdisciplinarily	
RI motivations	• Not harm human health and the environment • Create more efficient and effective products • Responsible innovation aligns with mission of discipline • Research integrity and ethics		*Purpose w.r.t. the public good* • Improve human well-being and/or solve societal problems	*Purpose w.r.t. the private sector* • Protect reputation • Avoid liability • Better understand and market your product

this theme, however, there were tensions surrounding who counts as a stakeholder and what ends are pursued through this stakeholder engagement. Some interviewees defined stakeholders mainly as industry and envisioned stakeholder engagement as a way to ensure that their products aligned with the interests of industry (e.g., see quote from *Engage Stakeholders* in Table 3), while others defined stakeholders more broadly and envisioned engagement as a way to ensure their products aligned with the public good (e.g., see quote from *Engage Stakeholders* in Table 1).

Reflexivity. Reflexivity — holding a mirror up to one's motivations and assumptions [10, 25] — took two main forms across researcher RI definitions, practices, and motivations. First, reflexivity was related to inclusion, as both interdisciplinarity and stakeholder engagement were discussed as ways to reflect on one's assumptions. As one academic researcher stated when discussing the importance of interdisciplinarity for reflecting on one's assumptions, "Working with people from diverse backgrounds, we learn more about experiments, too. We learn more about how the questions posed may or may not accurately answer exactly what you want to. And even if it answers certain things, what are the potential flaws in that argument?" Second, reflexivity was also present in the ways researchers articulated and considered their motivations for RI. There was a tension between researcher motivations related to the public good (*Improve human well-being and/or solve societal problems*) and those related to the private sector (*Protect reputation*, *Avoid liability*, and *Better understand and market your product*). The tension arises because one can pursue the latter three motivations while being agnostic as to whether the resulting product improves well-being or solves societal problems. That is, simply pursuing a marketable product that does not cause liability or reputation concerns is not the same as pursuing products that align with broader notions of the public good. One can see this tension in the different ways that the following two researchers articulate their motivation for RI. One industry researcher who focuses on liability said: "Well, number one, you know, we all have this big problem of liability concerns. For a company that is a very huge concern… We want to put out things which are not going to be indefensible in terms of liability. That simply would

be foolish." Another industry researcher viewed their motivation for pursuing RI in a broader lens: "What can I do to help the agricultural community? What can I do to help them be better and be safer? Versus waking up every morning and watching glyphosate commercials; who's going to sue who kind of deal… It's about helping others. And I can do that with nanotechnology. I can't do it with a chemical."
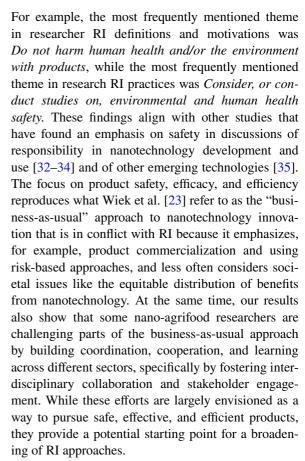
Responsiveness. Responsiveness — changing the direction of innovation based on stakeholder and public values and RI activities [10, 25] — was frequently present in researcher RI definitions, practices, and motivations, but mainly in implicit ways. For example, when researchers discussed the importance of conducting studies on product safety, efficacy, and efficiency, it was implied that the point was to make products more safe, effective, and efficient. Inclusion, in terms of interdisciplinarity and stakeholder engagement, was also seen as important for informing nano-agrifood innovation (see *Inclusion* above). Responsiveness emerged more explicitly in terms of public acceptability. As one academic researcher said: "When I am defining a new product or thinking about a new research project, the first thing that comes into my mind is always about feasibility and also the acceptability of the final products. We have to make sure that we encapsulate a specific compound that is publicly acceptable." This sentiment acknowledges the importance of having a market for one's product — i.e., not developing a product deemed publicly unacceptable. Yet, "the public" that researchers were being responsive to was framed in different ways by researchers. Some framed the public as an entity wanting safe products (e.g., that components of a nanotechnology are "food grade") while others framed the public as a potential barrier to technology that researchers deem as desirable, as one academic researcher said: "We don't want to end up in something that is similar to GMO which is good for some applications but still people are not accepting even though it is very powerful." Therefore, some researchers viewed the public as having legitimate concerns and other researchers viewed them as having illegitimate ones; either way, researchers thought they needed to be responsive to the public because of their potential to impact the uptake of technology.

Discussion and Conclusion

As the literature on RI has expanded over the past decade, a variety of potential RI definitions, practices, and motivations have emerged. This has resulted in a recognition of the importance of context when considering how to approach RI. For example, RI should be informed by differing national, cultural, epistemic, institutional, economic, regulatory, organizational, and technological contexts and circumstances [19, 20]. However, with so many definitions, practices, and motivations available, it is also possible that innovators pursuing RI may — consciously or not — take the path of least resistance when enacting RI. That is, researchers may primarily choose RI definitions and practices that align with what they are already doing, for example pursuing readily available toxicity testing rather than exploring new ways of incorporating inclusion and reflexivity into their innovation. Therefore, in addition to considering context, there is a need to consider the presence or absence of established RI principles when assessing what form RI takes. Van de Poel et al. [17] describe the need to combine a bottom-up approach that reflects realistic practices and circumstances "on the ground" or in a real-life case study, with a top-down approach that uses and applies acknowledged RI principles and practices. In our study, we attempted to fill this need by asking nano-agrifood researchers about their practices on the ground and tying them to key RI principles from the literature to look for congruencies and deficiencies. We show how efforts to understand and improve RI can be furthered by an analytical approach that pays attention to context while also considering overarching RI principles.

Our study contributes to the RI and nanotechnology literatures by identifying and analyzing how nano-agrifood researchers articulate RI definitions, practices, and motivations (Tables 1-4). We also examined how researcher RI definitions, practices, and motivations align with four prominent RI principles (i.e., anticipation, inclusion, reflexivity, responsiveness) (Table 5). We found that nano-agrifood researchers largely focused their discussion of RI definitions, practices, and motivations on the RI principle of anticipation, narrowly defined, however, in terms of product safety, efficacy, and efficiency. Far less frequently mentioned were other principles of RI, such as inclusion, reflexivity, and responsiveness.

For example, the most frequently mentioned theme in researcher RI definitions and motivations was *Do not harm human health and/or the environment with products*, while the most frequently mentioned theme in research RI practices was *Consider, or conduct studies on, environmental and human health safety*. These findings align with other studies that have found an emphasis on safety in discussions of responsibility in nanotechnology development and use [32–34] and of other emerging technologies [35]. The focus on product safety, efficacy, and efficiency reproduces what Wiek et al. [23] refer to as the "business-as-usual" approach to nanotechnology innovation that is in conflict with RI because it emphasizes, for example, product commercialization and using risk-based approaches, and less often considers societal issues like the equitable distribution of benefits from nanotechnology. At the same time, our results also show that some nano-agrifood researchers are challenging parts of the business-as-usual approach by building coordination, cooperation, and learning across different sectors, specifically by fostering interdisciplinary collaboration and stakeholder engagement. While these efforts are largely envisioned as a way to pursue safe, effective, and efficient products, they provide a potential starting point for a broadening of RI approaches.

Another key finding from our study is that when RI principles of inclusion, reflexivity, and responsiveness were present in researcher RI definitions, practices, and motivations, they contained noteworthy tensions. For example, the inclusion of stakeholders was seen by some researchers as a way to align products with the interests of industry and by others as a way to align innovation with the public good. Further, the purpose of RI was seen by some researchers as a way to protect reputation and avoid lawsuits and by others as a way to improve human well-being and solve societal problems. This tension between aligning RI with private industry and aligning RI with the public good has been noted in discussions about nanotechnology RI [26] and about RI more broadly [17, 36]. These tensions emphasize the need to carefully pay attention to how RI is envisioned, as the desire to "engage stakeholders" can be for very different ends. The goal of paying attention to how RI is envisioned should not be an invitation, however, to police RI and question all applications of RI that are in alignment with the private sector; indeed such alignments may open the space to explore

how private sector innovation can pursue a broader set of ends than just economic profit. Rather the goal should be to increase awareness of how RI is being envisioned and enacted in different contexts. Such awareness is essential to reflecting on what is at stake in how RI envisioned and enacted, as well as on what we should expect from RI in different contexts. To consider an example, if RI is widely being envisioned as unproblematically aligning with the interests of private industry, even in government and academic public institutions, this may indicate an imbalance in need of addressing; in this example, potentially, the trend of marketization and academic capitalism [16].

There are three important limitations of this study. First, most study participants from industry were from small-to-medium-sized companies, with only two participants from large companies. While we reached out to many individuals from larger food and agricultural companies, we found little interest to participate. Participation from more large companies may have revealed a broader set of views concerning nano-agrifood RI. Second, study participants all shared a commitment to RI; that is, none of our participants said they were not interested in RI. Different understanding of RI may have emerged from conversations with individuals who do not see RI as important. Third, we did not provide a definition of "responsible innovation" or "innovate responsibly" to study participants, since we were interested in their own views concerning what that term means in context of their nano-agrifood applications. A different approach that provided a host of existing RI definitions and related practices would have likely led interviewees to broaden their discussions of RI. While the lack of researcher familiarity with RI literature is a recognized challenge [17], it also makes clear the importance of researchers' own views on RI, which was the very purpose of this study.

We conclude by highlighting some of the implications of our study for RI, particularly within the nano-agrifood context. First, because of the different views nano-agrifood researchers hold concerning what constitutes RI and because of the narrow overall focus on product safety, efficacy, and efficiency, future RI efforts should foster discussions among researchers on what it means to responsibly innovate and what practices fall under the umbrella of RI within nano-agrifood sectors. These conversations can serve as a forum for researchers to understand the breadth of potential definitions and practices that exist, and can help nano-agrifood researchers grapple with the challenges they face in pursuing RI practices and how to navigate them. Particular work on tying the principles of reflexivity, responsivity and inclusion to the contexts of nano-agrifood researchers is needed, perhaps through collaborations between scholars that study RI and these researchers. As a starting point for broadening beyond a focus on product safety, efficacy, and efficiency, one could highlight and discuss the broader themes that emerged in our interviews such as engaging stakeholders, collaborating interdisciplinarily, and considering the purpose of RI. Second, we also recommend strengthening the institutionalization of RI principles to better and more effectively translate theoretical principles into tangible, concrete, and practical efforts. One version of this could be the integration of existing practical approaches to achieve RI principles such as value-sensitive design [37, 38]. This will help ensure researchers see the concepts of RI as realizable and not as abstract academic theories. This aligns with calls for more concrete guidance to translate the theoretical framings of RI into actions that can be taken within institutions conducting research, development, and innovation [e.g., 9, 18, 24]. Finally, future work could focus on applying this study's process to other technological fields relevant for food and agriculture sectors in order to explore how researchers and innovators envision and practice RI more generally.

Code Availability Not applicable.

Declarations

Ethics Approval This study received Institutional Review Board approval via NC State University (Protocol 19207).

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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