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Beyond the Hype: Stakeholder Perceptions of Nanotechnology and Genetic Engineering for Sustainable Food Production

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Abstract

Ensuring sustainable food systems is an urgent global priority as populations grow and environmental pressures mount. Technological innovations such as genetic engineering (GE) and nanotechnology (nano) have been promoted as promising pathways for achieving greater sustainability in agriculture and food production. Yet, the sustainability of these technologies is not defined by technical performance alone; it hinges on how they are perceived by key stakeholders and how well they align with broader societal values. This study addresses the critical question of how expert stakeholders evaluate the sustainability of GE and nano-based food and agriculture (agrifood) products. Using a multi-method online platform, we engaged 42 experts across academia, government, industry, and NGOs in the United States to assess six real-world case studies—three using GE and three using nano—across ten different dimensions of sustainability. We show that nano-based products were consistently rated more favorably than their GE counterparts in terms of environmental, economic, and social sustainability, as well as across ethical and societal dimensions. Like prior studies, our results reveal that stakeholders see meaningful distinctions between nanotechnology and biotechnology, likely due to underlying value-based concerns about animal welfare, perceived naturalness, or corporate control of agrifood systems. The fruit coating and flu vaccine—both nano-enabled—received the most positive ratings, while GE mustard greens and salmon were the most polarizing. These results underscore the importance of incorporating stakeholder perspectives in technology assessment and innovation governance. These results also suggest that responsible innovation efforts in agrifood systems should prioritize communication, addressing meaningful societal needs, and the contextual understanding of societal values to build trust and legitimacy.

Keywords: agrifood technologies; genetic engineering; nanotechnology; perceptions of sustainability; stakeholder engagement; responsible innovation; technology governance

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Academic Editors: Ping Dong and Long Yu

Received: 27 June 2025
Revised: 21 July 2025
Accepted: 23 July 2025
Published: 25 July 2025

Citation: Horgan, M.D.; Cummings, C.L.; Kuzma, J.; Dahlstrom, M.; Cimadori, I.; Cuchiara, M.; Larter, C.; Loschin, N.; Grieger, K.D. Beyond the Hype: Stakeholder Perceptions of Nanotechnology and Genetic Engineering for Sustainable Food Production. *Sustainability* **2025**, *17*, 6795. https://doi.org/10.3390/su17156795

1. Introduction

Food and agriculture (agrifood) systems are under growing pressures to deliver safe, plentiful, and nutritious food to support an increased global population, all while reducing environmental impacts and enhancing sustainability. Studies have estimated that the world's population will reach 10 billion people by 2050, and that we have already surpassed 6 out of 9 planetary boundaries in terms of safe operating zones for humanity [1]. Agricultural systems are facing mounting pressures due to the accelerating impacts of climate change, including more frequent and severe extreme weather events. Concurrently, consumer preferences are evolving, with growing demand for more ethical, sustainable, and animal-friendly livestock production practices. These converging trends underscore the urgent need to transform agrifood systems to enhance productivity while strengthening ecological resilience and advancing social responsibility. Without systemic innovation and the adoption of more sustainable practices, current agricultural models may become increasingly unsustainable, jeopardizing both global food security and environmental integrity.

These intersecting challenges indicate the urgent need to determine what types of innovations in sustainable food systems are most likely to address emerging global demands. Further, the adoption and assessment of such innovations are shaped by national contexts as cultural values, regulatory frameworks, and agrifood policy priorities vary across countries. Accordingly, this study centers on U.S.-based stakeholders to help inform how U.S. agencies and institutions might evaluate and govern emerging agrifood technologies in alignment with national interests. For example, in the U.S., federal agencies including the Food and Drug Administration (FDA), the United States Department of Agriculture's (USDA's) National Institute of Food and Agriculture (NIFA), and others proposed varying definitions and frameworks for sustainability in agrifood systems, often incorporating dimensions of environmental health, economic viability, and social equity to guide both public research funding and regulatory decisions while reflecting the complexity and context-dependence of sustainability as a concept [2]. In response, many innovations have been explored in recent years, including advances in alternative protein development, precision irrigation systems, climate-resilient crop breeding, and improved nutrient delivery mechanisms such as phosphorus efficiency technologies [3–9]. Amid this landscape, nanotechnology and genetic engineering have emerged as two particularly prominent and controversial approaches, each offering potentially transformative solutions for sustainable food production. Nanotechnology (nano) enables precision interventions at the molecular scale, while genetic engineering (GE) facilitates targeted modifications to plant and animal genomes. Both fields have been promoted by researchers and developers as means to improve agrochemical delivery, reduce waste, enhance food preservation, increase yields, foster climate resilience, and provide nutritional enhancements [10–14].

Despite their intended benefits, agrifood products using nano and GE have generated discussions and debates regarding their environmental, ethical, and societal implications as their value ultimately depends on how they are developed, deployed, and perceived by those who influence, regulate, and interact with them. Thus, it is critical to assess whether such products deliver on sustainability claims and how they are perceived by key stakeholders who influence the development, governance, and use of agrifood innovations. While numerous methodologies exist to evaluate technological innovation (e.g., life-cycle assessments, risk analyses, market forecasting), this study employs a systematic stakeholder engagement approach that relies on assessment of experts embedded in relevant sectors on developed nano- and GE-enabled agrifood products. These individuals shape scientific discourse, regulatory pathways, and public narratives, making their input vital for assessing the sustainability potential of GE and nano in agrifood systems. A robust evaluation framework to garner insights from stakeholders that accounts for multiple dimensions of sustainability can identify new opportunities for responsible innovation, improve legitimacy and trust in technological development, and contribute to broader scholarly and policy conversations around the governance of emerging agrifood technologies [15–19].

To navigate the complex tradeoffs and contested perceptions surrounding uses of GE and nano in agrifoods, our research is guided by the following overarching research question: *How do expert stakeholders perceive the sustainability of nano and GE when applied to agrifood systems?* To answer this question, we systematically evaluate and compare how expert stakeholders in the U.S. perceive the sustainability of real-world applications of GE and nano in agrifood products. We begin with a review of existing literature on how sustainability is defined in the context of agrifoods, synthesizing insights from diverse sources to identify ten distinct dimensions of sustainability: environmentally sustainable, economically sustainable, socially sustainable, responsible, useful, superior to alternatives, ethical, fosters a fair and just society, contributes to a collective good, and equitable. Next, we present a brief overview of the development and application of GE and nano in the agrifood sector. This review informs the selection of six real-world case studies: three involving GE and three involving nano. Using a multi-activity online engagement platform, we elicited evaluations of the sustainability of the six case studies from 42 U.S.-based stakeholders representing academia, industry, government, and civil society, which we then discuss within broader debates about responsible innovation, the governance of emerging technologies, and the future of sustainable food systems. By systematically examining stakeholder perspectives across a standardized framework of ten dimensions of sustainability, this study achieves two primary outcomes, (1) it advances understanding of how real-world applications of GE and nano are positioned within ongoing efforts to define and achieve sustainability in agrifoods; and (2) it provides novel theoretical and methodological contributions for sustainability assessment by offering a multidimensional framework that captures the complex and interrelated factors across diverse sustainability dimensions.

2. Literature Review

Understanding stakeholder perceptions of sustainability in emerging agrifood technologies requires grounding in two key areas of scholarship. First, we review how sustainability has been defined and operationalized in the context of agrifoods, drawing from this literature to develop a framework of ten distinct but interconnected dimensions of sustainability. This framework serves as the analytical foundation to guide expert stakeholders in evaluating novel technologies. Second, we examine the development and application of GE and nano within the agrifood sector. This includes a review of how these technologies have been used to date, as well as the extent to which their sustainability implications have been assessed.

2.1. Defining Sustainability in Agrifood Systems

Publications on sustainability have increased significantly over the past two decades, often structured around three foundational pillars: environmental, economic, and social sustainability [20]. These pillars are embedded in the United Nations' (UN) Sustainable Development Goals (SDGs) and the broader concept of "sustainable development", which spans domains from urban infrastructure to agrifood systems. In the U.S. agricultural context, these ideas are reflected in the USDA's 2011 consensus statement, which outlines sustainability as a balance of four goals: "satisfying human needs; enhancing environmental quality, the resource base, and ecosystem services; sustaining the economic viability of agriculture; and enhancing the quality of life for farmers, ranchers, forest managers, workers, and society as a whole" [2].

To define sustainability in our survey, we adopted definitions for each of the USDA's pillars of sustainable agriculture that align with established literature and policy frameworks. We defined environmental sustainability as the ability to preserve and protect the natural environment over time through appropriate practices, meeting present needs without compromising the availability of resources in the future. This reflects the Brundtland Report and longstanding U.S. environmental policy, such as the National Environmental Policy Act of 1969, which emphasizes achieving "productive harmony" between humans and nature [21,22]. We defined economic sustainability as the ability to preserve and promote long-term economic well-being, consistent with SDG 8, which calls for inclusive and sustainable economic growth and decent work for all [23]. Finally, we defined social sustainability as the ability to preserve and protect the well-being of people and communities, encompassing principles like equity, human rights, ethical labor, and community development. This aligns with the UN's framing of social sustainability as managing business impacts on people and reflects broader commitments to ethical, legal, and social implications (ELSIs) in responsible innovation.

While the UN's three pillars of sustainability—environmental, economic, and social—provide a foundational framework for understanding sustainable development, they are not always sufficient for evaluating the complexity of agrifood systems, particularly in the context of emerging technologies. The introduction of novel technologies into agrifoods is rarely judged on efficacy alone, as stakeholders bring to the table diverse concerns, values, and priorities that shape their views of what counts as "sustainable". As such, it is not sufficient to evaluate these technologies solely through environmental or economic lenses; rather, it is essential to incorporate a more granular and multidimensional view of sustainability that includes ethical, social, and justice-related considerations. A growing body of literature has argued for expanding the traditional sustainability framework to incorporate additional dimensions that better reflect the unique challenges and values across different sectors [24–26]. In the realm of agricultural biotechnology, scholars have increasingly emphasized the need for a more comprehensive and context-specific approach to sustainability assessment [27–30]. The latter studies surveyed U.S. stakeholders with subject matter expertise to better understand their attitudes towards additional parameters, including sustainability parameters that are important for assessing novel agrifood products. The studies revealed a clear demand for expanding conventional sustainability frameworks to include factors such as health impacts, ethical considerations, and long-term societal implications, underscoring the need for a more holistic and adaptive understanding of sustainability in this space.

To identify additional dimensions of sustainability that should be evaluated alongside environmental, economic, and social considerations, we reviewed existing literature on the tenets of sustainable agrifood systems. Sustainable agriculture is often linked to responsible and ethical behavior, especially when compared to conventional methods [31]. To be competitive with conventional agrifood products, it is also important that new products practical, useful, and offer some advantage over existing alternatives, such as agricultural products that produce higher yields while also minimizing chemical use in food production [32]. Finally, sustainable agriculture models like fair trade often promote values such as social justice, contributing to a collective good, fairness in labor practices, and equitable benefits, especially for marginalized producers and communities [33,34]. Hence, we added 7 additional dimensions to investigate the sustainability of agrifoods that include responsible, useful, superior to alternatives, ethical, fosters a fair and just society, contributes to a collective good, and equitable. These added dimensions are also supported by results from the previous research as well as considerations in several risk-benefit frameworks [30,35,36]. Together, we find our identified 10 dimensions of sustainability to fully encompass the USDA 2011 consensus statement on what constitutes sustainable agricultural systems.

2.2. Nano and GE as Approaches to Sustainable Agrifoods

The advancement of new and novel technologies, including the use of GE and nano, is largely seen as essential for driving scientific breakthroughs that promote sustainable futures, including those in agrifoods [37]. GE and nano are broad-reaching tools that can significantly enhance the precision with which we can modify, monitor, and optimize a wide variety of foods—from improving crop traits at the genetic level to delivering nutrients and detecting contaminants at the molecular scale. While many emerging technologies, such as alternative proteins, vertical farming, or synthetic biology, are reshaping sustainability in the agrifood landscape, GE and nano are examined in this study because they are already in active use across diverse agrifood applications, have well-established regulatory and scientific foundations, and continue to generate public and policy debate. These technologies are also broadly enabling, serving as foundational platforms for a wide array of downstream innovations in both plant and animal agriculture.

Genetic engineering (GE) refers to various techniques used to modify an organism's genetic makeup by adding, removing, or altering specific genes using modern biotechnology methods such as recombinant DNA, and in this paper, includes gene editing which uses these molecular methods to create the product (even if the foreign genes may be backcrossed out of the final product). By intentionally modifying or editing an organism's genetic material, GE can create crops with greater resistance to pests, diseases, and environmental stressors (such as impacts from climate change). GE foods and agricultural products are anticipated to enhance food safety, nutrition, and access to healthy foods, while promoting more sustainable and environmentally friendly agricultural practices [38,39]. Some GE crops are specifically engineered to withstand extreme weather conditions such as flooding and drought [11,40,41] and to facilitate more sustainable crop disease management [37]. In the context of livestock, gene editing may help accelerate the development of traits associated with improved welfare, such as polledness, while preserving other desirable genetic characteristics that might be lost through traditional selective breeding [42].

Nanotechnology (nano) refers to the field of science and engineering that creates, develops, and manipulates materials on the nanoscale, which is roughly 1–100 nm. At this very small scale, materials can have unique and different physical and chemical properties compared to the same materials on bulk scales. For over two decades, nano applications in agrifoods have been explored to improve sustainability through more efficient agrochemical delivery (e.g., nanopesticides, nanofertilizers), extend the shelf life of fresh-cut produce using nano-emulsion coatings to inhibit microbial growth, and enhance vaccine delivery for livestock via nano-vaccines [10,14,43–48].

Given the importance of understanding stakeholder perceptions and views of novel technologies in agrifood contexts, numerous studies have investigated the perceptions of GE and nano in agrifoods [19,49–53]. Among others, several studies have found that stakeholders raised concerns over the absence of multi-stakeholder collaborations in GE/agrifood development, the lack of transparent information about GE products, inadequate oversight, and potential gaps in regulatory systems [54]. For nano applications in agrifoods, previous studies have found stakeholder concerns related to uncertainties and data gaps related to understanding human health and environmental impacts of using engineered nanomaterials in agrifood systems [19,55,56], the lack of transparent information on their use in the food supply, issues of trust [57], and whether the product fulfilled a societal need [58]. Further, studies have found that the public is more willing to accept nanomaterials in packaging materials than inside the food and for purposes of preventing spoilage or enhancing nutrition than for taste or cheaper production [59–61]. Consumers also place strong value on labeling nanofood products, but do not prioritize nano labeling as high as GE food labeling [62]. When comparing nano applications to GE applications for food, consumers are willing to pay more to avoid GE foods than to avoid nanotech foods, but for both technologies, prefer applications directed towards nutrition and safety benefits over environmental or taste benefits [51,62–64]. For both technologies, trust in government to manage the technologies influences consumer willingness to accept nano and GE foods [64].

While many have begun to assess stakeholder perceptions of GE and nano in agrifood products, there is an absence of deeper and more inclusive assessments of the degree to which GE and nano contribute to sustainable agrifood systems. Hence, our study provides an important step forward by operationalizing a multidimensional evaluation of sustainability grounded in expert stakeholder input. Rather than relying solely on conventional metrics or top-down assessments, we designed a method that foregrounds how sustainability is interpreted and applied by those with lived experience and professional expertise across the agrifood landscape. By presenting stakeholders with detailed case studies of actual or near-market GE and nano applications, and by asking them to evaluate these across ten specific sustainability dimensions—including environmental, economic, social, ethical, and justice-based criteria—this research captures a more textured and realistic view of how emerging technologies are judged in context. The findings not only offer practical guidance for innovators, regulators, and funders, but also contribute conceptually to the growing literature on responsible innovation and sustainability science. In doing so, our study, described in detail below, helps to identify where opportunities and tensions lie, where greater clarity or communication may be needed, and where stakeholder priorities may diverge across technological approaches. It ultimately serves as a foundation for more responsive, trustworthy, and societally aligned pathways for advancing sustainable agrifood systems.

3. Methods

To investigate stakeholder perceptions of GE and nano-based agrifood products through the lens of sustainability, we employed a multi-phase tailored design survey presented via a custom-built online engagement platform [65,66]. This platform was designed to facilitate structured, multi-step interaction with expert stakeholders across a range of sectors, including academia, government, industry, and non-governmental organizations. Participants were presented with detailed case studies of six real-world products, three involving GE and three involving nano, and asked to evaluate each across ten distinct dimensions of sustainability. The convergent mixed methods study combined quantitative survey data with open-ended qualitative responses and online discussion forums, allowing for both standardized comparison and deeper insight into the reasoning behind stakeholder judgments [67]. This approach enabled us to capture both individual assessments and broader patterns across the sample, offering a comprehensive view of how sustainability is perceived in practice across diverse technological applications.

3.1. Respondent Sampling Procedure

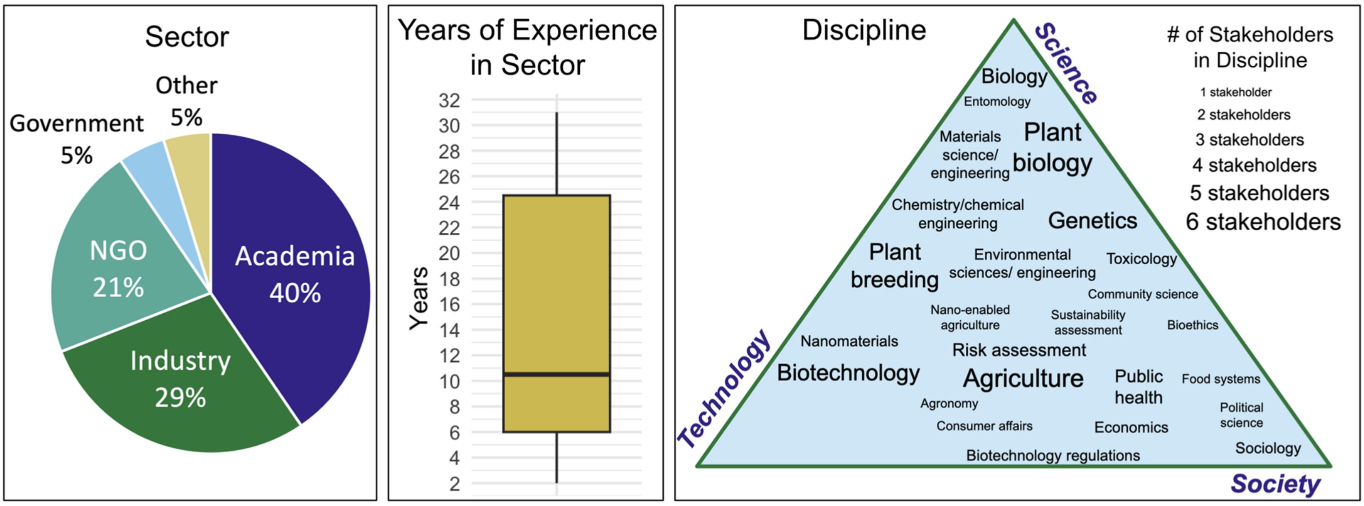
Potential stakeholders were selected by identifying experts associated with topical peer reviewed literature (e.g., journal article publications, organizational reports), conferences and workshops, USDA's Current Research Information System (CRIS) database, as well as the research team's networks within GE, nano, food science, agriculture, veterinary medicine, and governance areas. The aim was 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), and government agencies. In total, the research team identified 570 individuals with the goal of having 60–75 stakeholder participants accept the invitation to participate in this study. Before reaching out to participants, the research team submitted the survey protocol to the research institutions under which the research took place (NC State: IRB ID 26701; Iowa State: IRB ID 24-038), which deemed the research IRB exempt.

Identified stakeholders were contacted via email with a brief description of the project and the reason for contacting them. Interested stakeholders were given a consent form that outlined an overview of the project, what they will be asked to do in the participation process, risks, benefits, aspects of confidentiality, compensation, and contact information. After consenting, participants were given a temporary username and password with instructions on how to access the website and complete the activities. 61 people consented to the study, of which 51 completed at least part of the study and 42 completed the study in full. Participants received an honorarium of $100 to complete all activities in the study.

3.2. Sample Composition

As the purpose of this study was to sample a diverse range of expert stakeholders from sectors in or adjacent to relevant fields, the priority of sampling was less on ensuring a representative sample and more on ensuring that the sample included representation from a significant proportion of fields. Of the 42 participants that completed the study 12 came from industry, 17 from academia, 2 from government, 9 from NGOs, 1 from "consulting" and one a member of a "think tank" (see Figure 1a). Participants ranged from 2 to 31 years of work within their sector with the average being 14.6 and a positive skew of a 10.5-year median (see Figure 1b). Participants were asked to report on their areas of expertise and disciplinary knowledge. The majority of participants selected more than one option with half identifying expertise in crop or agricultural sciences, half identifying expertise in natural sciences, one quarter identifying expertise in social sciences, and 2 participants reporting expertise in law. A compilation of the disciplines mentioned, mapped by their relation to the domains of science, technology, and society and size corresponding to the number of participants who listed the sector, is found in Figure 1c. Much of the population in this field is highly connected to each other so for the sake of protecting participant identity, we only collected demographic information on their areas of expertise and discipline, and their position within those areas.

While our sample of 42 U.S.-based stakeholders is comparable in size to similar studies in the literature, the modest sample limits the generalizability of the findings. We sought to ensure balance across stakeholder sectors, but representation from the government sector was notably lower, and the participant pool overall skewed toward individuals actively engaged in or supportive of biotechnology, potentially underrepresenting more critical or skeptical voices. Additionally, it should be noted that this study focused on U.S. agricultural systems and policy contexts, and therefore recruited stakeholder participants in the U.S. While this allowed for in-depth engagement with individuals familiar with domestic regulatory frameworks, markets, and cultural expectations, we recognize that perceptions of sustainability, particularly in relation to emerging technologies, may vary considerably across countries due to differences in governance structures, food systems, and public attitudes.



(**a**) (**b**) (**c**)

Figure 1. Demographic data for the 42 study participants, including (**a**) the sector they belong to, (**b**) years of experience in that sector, and (**c**) a conceptual representation of the depth and breadth of disciplines represented by the stakeholders.

3.3. Case Studies

To facilitate a structured and comparative assessment of stakeholder perceptions, we developed six detailed case studies, three focused on GE products and three on nano applications, each selected to represent different sectors within agrifoods. The goal was to present real-world or near-market examples that reflect the diversity of innovations being pursued under the umbrella of sustainable agrifood technologies. Case selection was guided by three primary criteria: (1) relevance to ongoing scientific and commercial development, (2) diversity in application across plant, animal, and agricultural innovations, and (3) variation in the type of sustainability benefit targeted (e.g., environmental protection, food security, animal welfare, nutrition). After initial selection, each case was subjected to extensive review and background research using peer-reviewed literature, regulatory reports, and public communications to ensure technical accuracy and contemporary relevance. How the case studies were presented to participants is described in the following section. This is followed by a summary of each case study, with full case study descriptions found in Supplementary Information.

3.3.1. Case Study Portrayal

Each case study document was carefully designed to be approximately two pages in length, following a standardized format that included: (1) the context and purpose of the product, (2) a plain-language explanation of how GE or nano was used, and (3) a summary of anticipated benefits and potential risks. This structure allowed for cross-case comparability while ensuring accessibility to a wide range of stakeholders with diverse disciplinary backgrounds. Relevant references were cited throughout to support factual claims and to encourage transparency and replicability. Importantly, we worked to minimize framing bias in the presentation of the cases. Information was presented in a neutral, evidence-based tone, and we carefully balanced descriptions of potential risks and benefits. The language avoided emotive or speculative phrasing and refrained from normative judgments. Each draft underwent multiple rounds of revision by the research team, including content experts and social scientists, to ensure the final versions were concise, balanced, and appropriately nuanced. The final cases included GE applications such as faster-growing Atlantic salmon, heat-tolerant beef cattle, and less pungent mustard greens;

and nano-enabled products such as phosphorus-efficient fertilizer, nanoencapsulated avian flu vaccines, and fruit coatings designed to increase shelf life and reduce waste. By presenting these case studies in a uniform, digestible, and unbiased manner, we aimed to elicit informed stakeholder evaluations across a range of sustainability dimensions in the subsequent phases of the study.

After stakeholders expressed interest in participating in the study, they were provided with anonymized, temporary login credentials to access a secure, custom-built online engagement platform. The platform guided participants through a series of five structured activities designed to gather both quantitative and qualitative insights. In Activity 1, participants completed a Qualtrics-embedded survey that collected demographic information, including their professional sector and areas of expertise or disciplinary background. This survey also included a previously validated set of scale items designed to measure participants' trust in science and technology [68]. In Activity 2, participants reviewed product overview documents for each of the six case studies, three involving GE and three involving nano—and then completed short surveys assessing their perceptions of each product's potential risks and benefits. These dimensions included human health, animal health, environmental impact, and ethical, legal, and social implications (ELSIs), as well as their level of certainty in those judgments. Participants repeated this process across all six case studies. In Activity 3, after completing all individual case assessments, participants completed a final survey capturing their holistic perceptions of each product's sustainability and potential for overall benefit or harm. This survey also included open-ended prompts about actions developers or regulators could take to address any concerns. Finally, Activity 4 consisted of an asynchronous discussion board where participants shared and responded to others' perspectives on two central prompts related to technology governance and the role of GE and nano in sustainable agrifoods.

This article focuses on stakeholder assessments of sustainability regarding Activity 3 of the platform. In this activity, participants were asked to evaluate each of the six case studies across ten dimensions of sustainability: environmentally sustainable, economically sustainable, socially sustainable, responsible, useful, superior to alternatives, ethical, fosters a fair and just society, contributes to a collective good, and equitable. These dimensions were presented using semantic differential scales, with three of the most conceptually significant terms (environmental, economic, and social sustainability) accompanied by hover-text definitions to ensure shared understanding. This design enabled a multidimensional and comparative assessment of each product's perceived sustainability profile, generating rich data that could be analyzed quantitatively and contextualized through earlier responses and discussion board contributions.

3.3.2. GE Case Studies

Case Study 1: Faster-Growing Atlantic Salmon

Faster-growing Atlantic salmon ("AquAdvantage Salmon") is an FDA-approved transgenic organism engineered by AquaBounty. It incorporates the Chinook salmon's growth hormone gene to grow Atlantic salmon faster compared to its non-GE counterpart [69,70]. The potential advantages of this GE salmon include an increase in seafood production to meet increased demand, a year-round growth, and potential to increase aquaculture sustainability through more efficient feed utilization as well as a prospected pressure reduction on wild salmon stocks. The FDA concluded that AquAdvantage Salmon and the derived foods are as safe to eat as food derived from non-GE Atlantic salmon since they have largely equivalent nutritional profiles [69]. Despite its approval, some have voiced concerns about the adequacy of the FDA assessment, particularly with regard to the risk of uncontrolled release [71]. These concerns persist despite several proactive measures taken to prevent escape: the GE salmon is only authorized to be grown in land-based facilities (one in Indiana, one in Canada) with highly sophisticated containment systems, and only sterile females are grown [69]. Additionally, a 2019 study reported a general more negative consumer perception for the GE salmon compared to GE vegetables [72]. Another study came to a similar conclusion, pointing to the fact that in general consumers appear to be more concerned with the use of biotechnologies in animals compared to plants, and concerns for animals include animal welfare and gene editing animals for productivity traits [73]. As of 2025, AquaBounty has ceased the fish farming operations due to lack of funds to maintain the operation [74].

Case Study 2: Heat-Tolerant Slick-Hair Beef Cattle

Heat-tolerant slick-hair beef (SLICK) cattle originate from two founder beef calves that were gene edited with Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) to achieve a haircoat that allows them to stay comfortable in warmer temperatures [75]. The founder cattle were modified by making a heritable edit to the prolactin receptor gene (i.e., PRLR gene), shortening the prolactin receptor protein in cattle to mimic a trait present in many breeds of cattle commonly found in tropical and subtropical areas [30,75]. Potential benefits of these GE cattle include faster introduction of the trait compared to traditional selective breeding, the ability to expand cattle production into previously unsuitable regions, and improved adaptability to rising temperatures—potentially enhancing animal welfare. PRLR-SLICK cattle are the first low-risk determination and decision to exercise enforcement discretion for an Intentional Genomic Alternation (IGA) in animals for food use. FDA risk evaluations concluded that there are no known safety risks from the PRLR-SLICK cattle food. Notably, the regulatory process for these GE cattle was less extensive than the GE salmon, as the SLICK cattle are not transgenic, as the edit did not involve DNA from other species [30]. The FDA also concluded that there is low environmental risk as many conventionally raised cattle in the US already have the trait, animal escape is unlikely (and easy to remedy if it occurs), and there are very few feral cattle populations in the US [75]. The agency therefore used its "enforcement discretion" in March 2022 to review the PRLR-SLICK cattle under a less extensive approval process [30]. Despite the overall low risks presented by the GE cattle to consumers and the environment, important considerations appear to be missing from FDA's risk assessment, including a lack of clear data concerning the actual welfare of the SLICK cattle. Additionally, the environmental risk section did not address potential land use and agrochemical impacts, and what a production expansion might imply for the environment should that occur (although there are no clear data on whether the SLICK cattle would lead to an increase in production and consumption). Lastly, similarly to the AquAdvantage salmon, studies point to the fact that the public perception of GE animals is generally more negative compared to GE plants due to concerns including animal welfare and misguided substitutes for conventional husbandry practices [42,73].

Case Study 3: Less Pungent Mustard Greens

Researchers at Pairwise (now overseen by Bayer) developed genetically engineered mustard greens (*Brassica juncea*) to alter the flavor to be less pungent and bitter than the conventional variety [76,77]. CRISPR was utilized to target and alter base pairs in the genes that are responsible for some of the pungent and spicy flavor that happens when eating the greens raw [76]. Multiple genes were targeted in the modification across seven chromosomes, including the deletion of two whole genes, blocking the conversion of glucosinolates to pungent oils. While normal cooking methods can break down the oils responsible for pungency [78], the anticipated benefit of the GE mustard greens is to increase the consumption of raw nutritious leafy greens. An anticipated risk of the GE mustard greens is related to change in glucosinolates, which are responsible as a plant defense mechanism against insects [79]. This decrease in glucosinolates may increase vulnerability to insects and in turn lead to an increase in pesticide use. Despite this risk, the GE mustard greens were found to be exempt from regulation, both in accordance with the Coordinated Framework for the Regulation of Biotechnology (CFRB) by USDA-Animal Plant Health and Inspection Service (APHIS) under the Plant Protection Act (PPA) [30] and under the now previous SECURE Rule with a Regulatory Status Review (RSR) [80]. Public opinion has shown that most people are more accepting of cisgenic modification rather than transgenic when it comes to GE techniques [81]. However, conventionally bred products are still preferred [82,83]. Concerns may center around the lack of labeling and regulation because of the use of gene editing and the National Bioengineered Food Disclosure Standards require foreign DNA in the final product for labeling [30]. The GE mustard greens were the first CRISPR agrifood product to be launched in North America.

3.3.3. Nano Case Studies

Case Study 4: More Efficient Phosphorus Fertilizer

Nano-based fertilizers have been developed and commercialized for agricultural applications to improve the efficiency of plant nutrient delivery, including phosphorus (P) [46]. Enhanced efficiency can increase crop yields while reducing nutrient runoff into the surrounding environment. To create a nanoscale encapsulated P fertilizer, engineered nanoparticles composed of polyamidoamine (PAMAM) dendrimers are mixed with conventional fertilizers [84,85]. The nutrient molecules in the fertilizer solution are attracted to the PAMAM dendrimer coating, forming an outer layer. The resulting mixture is then applied to crops, with electrostatic forces preventing nutrient leaching or premature binding to the soil, enabling efficient uptake by plants [86]. By improving the effectiveness of traditional fertilizers, nanoencapsulated P fertilizers could enhance plant growth and crop yields as well as help reduce economic losses for farmers [87]. Additionally, more efficient P delivery systems may benefit the environment and society by decreasing P runoff and agricultural pollution, thereby reducing the risk of eutrophication and harmful algal blooms, which can negatively affect human health, animal health, and ecosystems [46]. Currently, many uncertainties remain regarding the potential risks of nanoencapsulated P fertilizers to non-target environmental organisms and human health. While no toxicity or ecotoxicity studies have specifically examined PAMAM dendrimers loaded with P, research on PAMAM dendrimer nanoparticles and other nanomaterials suggests possible adverse effects on aquatic invertebrates, green algae, microorganisms, and zebrafish embryos [88–90]. Significant data gaps persist in understanding the environmental, health, and societal implications of nano-based fertilizers, and as of now, there are no nano-specific fertilizer regulations in the U.S. Although few studies have explored public perceptions and acceptance of nanoencapsulated fertilizers, broader research on nano applications in agriculture suggests moderately positive public support. Despite limited familiarity with nano products, many consumers perceive agricultural nano (e.g., nanopesticides) as offering greater efficiency and lower environmental impact compared to conventional agrochemicals. A majority also support continued development and use of nano in agriculture, as well as labeling nanoscale ingredients and additives in food products [62].

Case Study 5: Improved Avian Influenza Vaccines

Researchers are actively developing nanoencapsulated vaccines to combat poultry diseases, including avian influenza. This highly contagious disease poses significant economic challenges in the U.S. due to poultry mortality and trade restrictions imposed on infected flocks [91]. While several vaccines have been developed to address avian influenza, many have shown limited effectiveness. Polyanhydride nanoparticles (PANs) are synthetic, biodegradable copolymers with mucoadhesive properties, allowing them to adhere to cell membranes and enhance vaccine delivery. When used in vaccines, these nanoparticles enable a sustained release of antigens, potentially improving immune responses [47]. The use of PANs as a vaccine delivery system has been approved by the FDA for human applications, and the vaccine is considered safe for poultry. This is largely due to PAN's biodegradable nature, breaking down into nontoxic, metabolizable byproducts [92]. Ongoing research aims to assess the full range of benefits and potential impacts associated with nanoencapsulated vaccine delivery in poultry. While no toxicological risks of PANs have been reported in existing studies [47,93], their long-term effects on health and the environment remain largely unexplored. Available research suggests that stakeholders generally find their use in animal husbandry more acceptable than nanomaterials incorporated directly into food products or non-essential applications. While some consumers appreciate the increased oversight of animal health and welfare, others may express concerns about the presence of vaccine-related materials in food products.

Case Study 6: Fruit Coatings Designed to Increase Shelf Life and Reduce Waste

Researchers have developed and patented a nanocellulose-based coating designed to extend the shelf life of fresh produce, maintain freshness, and reduce food waste [48]. Nanocellulose is a natural, edible, biodegradable biopolymer derived from plant materials. To create a nanocellulose-based coating, cellulose nanofibers are extracted from plant biomass and then combined with other ingredients before being dispersed in water to form a coating solution [94]. The solution can be applied to fresh produce [48]. Extending the shelf life of fresh produce can significantly reduce food waste. Various forms of cellulose have been used in food for decades, and the FDA has classified bacterial cellulose and microcrystalline cellulose as Generally Recognized as Safe (GRAS). Unlike conventional food coatings, nanocellulose-based coatings provide an enhanced protective barrier against moisture loss, gas exchange, UV light, and microbial contamination, which can improve water retention and inhibit microbial growth [95]. However, the potential health and environmental risks of nanocellulose remain largely uncertain. While some studies have found no toxicity even at high concentrations, others have reported potential adverse effects, including inflammation, oxidative stress, and disruptions to gut microbiota [96–98]. Due to limited data, cellulose nanofibers have not yet received a GRAS designation. Few studies have examined consumer attitudes toward nanocellulose coatings on fresh produce. Existing research suggests that public acceptance is lower for applications where nanocellulose is directly ingested (e.g., coatings on fresh fruits) compared to non-ingested uses, such as removable food packaging.

3.3.4. Quantitative Comparison of the Sustainability of Case Studies

The data analysis presented in this paper is based on a set of questions from Activity 3 that asked stakeholder participants how they would rate each case study related to 10 dimensions of sustainability: environmentally sustainable, economically sustainable, socially sustainable, responsible, useful, superior to alternatives, ethical, fosters a fair and just society, contributes to a collective good, and equitable. For each item, stakeholders chose from five positions on a scale ranging from negative sentiment (e.g., unsustainable) to positive sentiment (e.g., sustainable). We categorized the responses into three groups: neutral (center of the scale), negative sentiment (the two positions closer to the negative sentiment word), and positive sentiment (the two positions closer to the positive sentiment word). To clearly capture the positive, neutral, or negative orientation of stakeholder views, we recorded participant responses from a 5-point scale to a 3-point scale to better align with overall sentiment toward sustainability. Specifically, responses of 4 or 5 were classified as sustainable (recoded as 3), 3 as neutral (recoded as 2), and 1 or 2 as unsustainable (recoded as 1). An example survey question can be found in Figure 2, with colored boxes exemplifying our grouping schema.

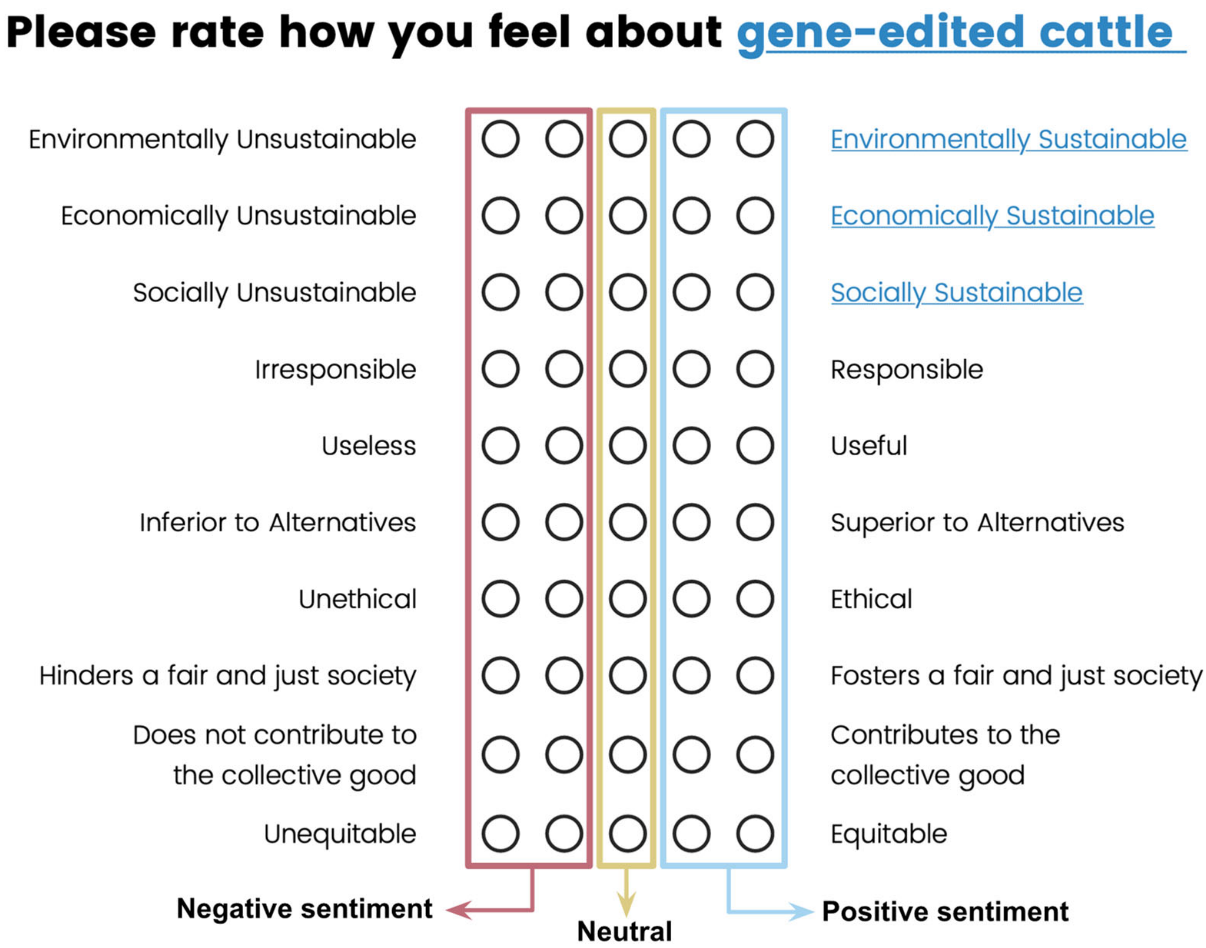


Figure 2. Example survey question with categorization. Blue text indicates terms that, when hovered over, displayed the definition used by our research team.

Using the new 3-point sentiment scale, we calculated the mean sustainability score for each case study across each of the ten dimensions, as shown in Table 1. These scores were used to generate 10 bar charts—one for each of the 10 dimensions of sustainability—that compare the proportion of positive, neutral, and negative sentiments about each of the six cases (Figure 3). These visualizations helped highlight specific strengths and weaknesses in each case study's perceived sustainability profile, offering a foundation for the more nuanced interpretation that followed. The raw data, including the frequency of each sentiment (sustainable, neutral, unsustainable) across all ten dimensions and six case studies, is available in the Supplemental Materials.

To explore whether the ten sustainability dimensions could be meaningfully combined into an overall sustainability factor, we examined how each dimension related to one another across the six case studies. Using the corrplot package in R, we generated a correlation matrix and plot (see Figure 4 in the Results and Table S11 in Supplementary Information), which visualized the strength and direction of linear relationships between each pair of dimensions based on their average scores on the original 1- to 5-point scale. The analysis revealed that all ten dimensions were positively correlated, with no correlation falling below 0.7, indicating that the dimensions tended to trend together and likely reflect a common underlying construct of sustainability.

Table 1. Mean sustainability scores for each dimension of sustainability across each of the 6 case studies (G = genetic engineering, N = nanotechnology). Scale = 1 to 3, with 1 being unsustainable and 3 being sustainable.

	Salmon (G)	Cattle (G)	Mustard Greens (G)	Fertilizer (N)	Flu Vaccine (N)	Fruit Coating (N)
Environmentally Sustainable	2.38	2.48	2.43	2.69	2.48	2.74
Economically Sustainable	2.64	2.67	2.62	2.62	2.62	2.74
Socially Sustainable	2.33	2.48	2.60	2.52	2.57	2.60
Responsible	2.50	2.60	2.50	2.64	2.79	2.67
Useful	2.71	2.76	2.52	2.83	2.91	2.86
Superior to Alternatives	2.38	2.45	2.29	2.57	2.83	2.64
Ethical	2.52	2.57	2.51	2.62	2.79	2.69
Fosters a fair and just society	2.38	2.42	2.32	2.37	2.45	2.57
Contributes to a collective good	2.52	2.49	2.49	2.69	2.81	2.69
Equitable	2.41	2.44	2.44	2.42	2.57	2.64

While the ten dimensions trend together and collectively represent an overall picture of sustainability, examining them individually offers valuable insights into specific areas where each product was assessed differently in each dimension. To better understand and visualize these differences, we developed the bar charts seen in Figure 3 by calculating the percentage of sampled stakeholders that rated their sentiment of a dimension as either sustainable, neutral, or unsustainable. Repeating this calculation for each of the ten dimensions across all six products, results in a measure of all three sentiments for all ten dimensions for each product that can be used to rank products by individual dimensions (See Figure 3) or overall assessed sustainability (See Figure 5). To support and contextualize findings about individual products, we triangulated our quantitative results with participants' open-ended responses collected in text-based sections of the surveys.

4. Results

This study aimed to answer the central research question: *How do expert stakeholders perceive the sustainability of nano and GE when applied to agrifood systems?* Drawing from quantitative ratings (and major claims supported by qualitative responses), our results offer a multidimensional view of how expert stakeholders evaluate these technologies across a range of real-world case studies. The findings illuminate key differences in perceived sustainability between nano and GE applications, as well as the specific sustainability dimensions—environmental, economic, social, ethical, and others—that shape stakeholder judgments. We begin by presenting the quantitative data, comparing stakeholder ratings of the six case studies across ten sustainability dimensions. Where appropriate, we incorporate qualitative insights from open-ended responses and online discussion board interactions to further contextualize these assessments. Together, these findings shed light on the factors that contribute to stakeholder evaluations and offer a deeper understanding of how sustainability is interpreted in the context of emerging agrifood technologies. An overview of the positive, neutral, and negative sentiments toward each of the 10 dimensions of sustainability is presented in Figure 3. Raw data is available in the Supplementary Information in Tables S1–S10.

First and foremost, most respondents viewed all six case studies as generally sustainable across the 10 dimensions. For both nano and GE applications, over half of stakeholders selected positive ratings for most sustainability dimensions, suggesting a broad openness to emerging technologies in agrifoods. This overall favorability coexisted with more nuanced differences; nanotech products were more consistently rated as environmentally and economically sustainable, socially beneficial, and ethically sound, while GE products, though still often rated positively, drew more mixed and uncertain responses, particularly around fairness, ethics, and social responsibility.

Consistent trends emerged across the dimensions with respect to nano- vs. GE-based products. Nano-based products were consistently rated more favorably than those developed through GE. When comparing stakeholder assessments across the ten dimensions of sustainability, nano products dominated the top rankings in several key areas. In five of the ten categories—responsible, useful, superior to alternatives, ethical, and contributes to a collective good—the three highest-rated products were all nano-enabled. The nano-based fruit coating received the highest scores in environmental, economic, and social sustainability, as well as in fostering a fair and just society. Meanwhile, the nanoencapsulated avian influenza vaccine ranked highest in the remaining six categories, including responsibility, usefulness, ethicality, and equity. In contrast, the three GE case studies were more uneven in their evaluations, with stakeholders expressing greater caution, particularly around issues of equity, environmental impact, and other ethical concerns.

The fairness and justice dimension revealed the most uncertainty overall, with no product receiving a clear endorsement. Still, the fruit coating stood out as relatively more favorable, while the GE products attracted the most skepticism. Similarly, the equity dimension produced mixed responses, with nanotech products again rated higher than their GE counterparts. The GE products, especially mustard greens and salmon, often prompted concerns or neutral stances regarding their ethical standing, societal value, and environmental or economic implications. Taken together, these results suggest that nano-based innovations in agrifoods are perceived as more aligned with sustainability goals than genetically engineered options.

Further analysis revealed that the ten sustainability dimensions included in this study were strongly positively correlated, with no pairwise correlation falling below 0.7 (see Figure 4 and Supplementary Information Table S11). This finding suggests that stakeholder perceptions of sustainability across these dimensions tend to move together, supporting the idea that they form a coherent and internally consistent construct. These results are particularly meaningful in light of calls from the literature to broaden traditional three-pillar models of sustainability—environmental, economic, and social—when evaluating agrifood technologies. Prior research has emphasized the need to incorporate additional considerations such as ethical responsibility, practical utility, fairness, and collective well-being [24–26]. The strong correlations observed here indicate that these expanded dimensions resonate with stakeholders as interconnected elements of sustainability, rather than isolated or conflicting concerns. This convergence reinforces the relevance of using a more holistic framework to assess the sustainability of novel agrifood products.

% = percent of stakeholders who selected each sentiment (sustainable, neutral, unsustainable)

Figure 3. Stakeholder sustainability assessments across ten dimensions. Each bar chart represents one dimension of sustainability, showing the percentage of responses rated as "sustainable" (positive), "neutral", or "unsustainable" (negative) for each of the six case studies. Cases are ordered independently for each dimension, from highest to lowest percentage of sustainable responses. In most dimensions, the nano cases appear closer to the top and GE cases appear at the bottom.

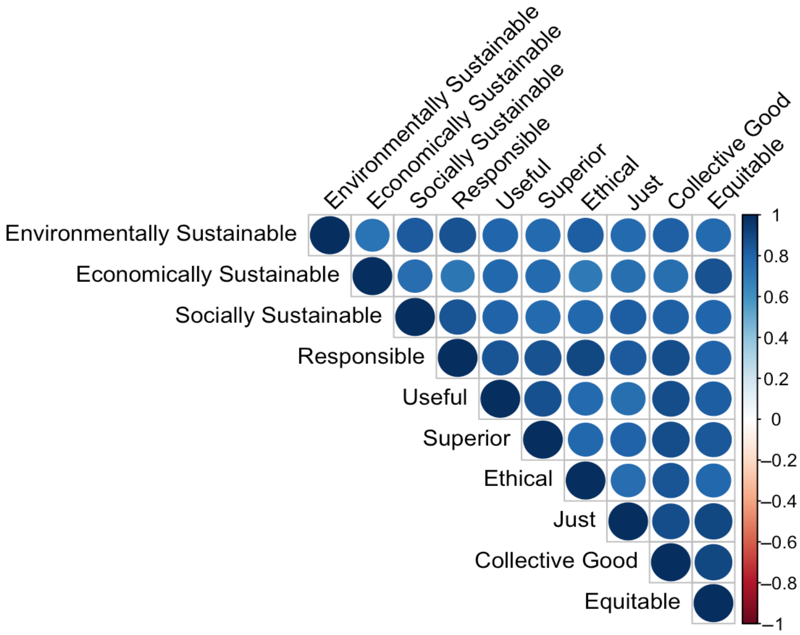


Figure 4. Correlation plot for the 10 dimensions of sustainability of all products. All 10 trend together, with no two dimensions having a correlation of less than 0.7. Raw correlation data can be found in Supplementary Information.

Because the ten sustainability dimensions trend together so closely, we calculated an overall sustainability profile for each case study by aggregating responses across all dimensions. For each case, we examined the total percentage of responses that were categorized as sustainable, neutral, or unsustainable across all ten categories. This aggregation offers a high-level summary of how each case study was perceived in terms of sustainability, providing a useful starting point for a comparison of the relative sustainability of the case studies, as seen in Figure 5.

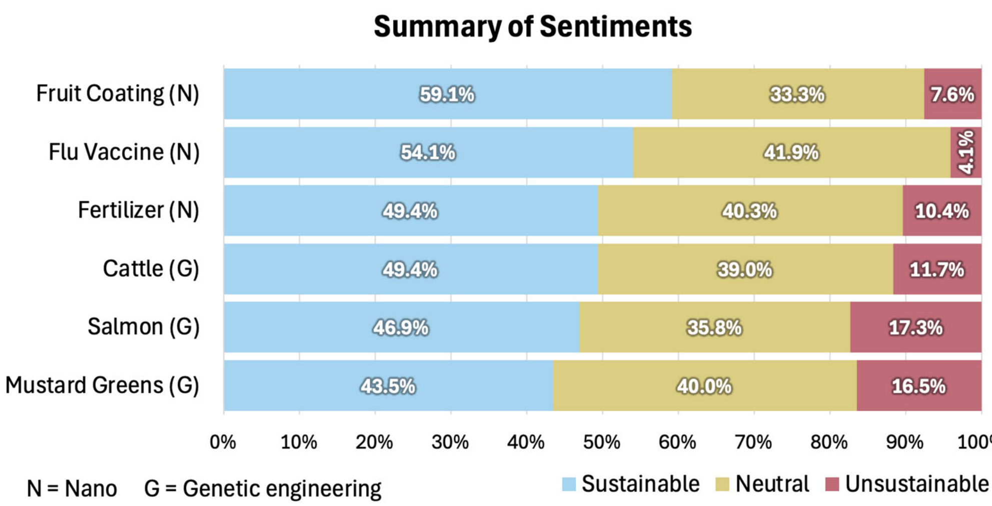


Figure 5. Summary of overall sustainability sentiment for all 6 case studies.

5. Discussion

The future of agrifoods depends on the development of systems that are both productive and sustainable, being capable of meeting global food demands while safeguarding environmental resources, promoting social equity, and building resilience to climate disruption. As the world population grows and ecological pressures intensify, innovations like

GE and nano are often positioned as promising tools to help achieve these goals. However, the true value of such technologies cannot be determined by technical performance alone. Their potential for contributing to sustainability must also be understood through the perceptions of stakeholders who influence development, governance, and public legitimacy. This study contributes to that understanding by offering the first empirical analysis of how expert stakeholders evaluate GE and nano-enabled agrifood products using a consistent, multidimensional sustainability framework.

It is first important to note that the majority of stakeholders viewed most of the products presented in this study as sustainable. For all six case studies, over 50% of respondents selected positive ratings for most sustainability dimensions, indicating a favorable overall orientation toward both nano and GE as tools for advancing sustainability in agrifoods. This widespread positive sentiment is encouraging, as it suggests that expert stakeholders see meaningful potential in these technologies to contribute to environmental, economic, and social goals. However, there were a few notable exceptions. Specifically, less than half of respondents rated the gene-edited mustard greens as environmentally sustainable or superior to conventional alternatives, and fewer than 50% rated either the nano-based phosphorus fertilizer or the mustard greens as equitable. Importantly, these lower scores were generally driven by an increase in neutral rather than negative sentiment. Across all ten dimensions and six products, negative ratings were uncommon—rarely exceeding 15% of responses. When they did occur, they were most likely to appear in evaluations of the genetically engineered salmon and the mustard greens. The salmon may elicit more polarized views due to its higher public visibility, regulatory controversy, and associations with transgenics and animal biotechnology. In contrast, the muted support for mustard greens may reflect stakeholder skepticism about whether improved taste alone constitutes a meaningful sustainability contribution, particularly when compared to products offering more clearly articulated environmental or health benefits. These findings highlight that while broad support exists, stakeholders apply discernment based on perceived impact, benefit type, and alignment with sustainability values—reinforcing the need for nuanced, context-specific engagement around emerging technologies.

Among the ten sustainability dimensions evaluated, “usefulness” stood out as the one with the greatest consensus and confidence among stakeholders. All six products were rated as useful by a clear majority of participants, with positive ratings above ~70% and neutral responses below 20% in every case. Four of the six products, three nano-enabled and one GE—were rated as useful by over 85% of stakeholders. This strong agreement suggests that expert stakeholders generally view these technologies as having a clear function or purpose within the agrifood system. The consistency of this response, regardless of whether a product was rated highly on other dimensions, indicates that “usefulness” may serve as a baseline or threshold consideration for innovation: if a product is not viewed as useful, it is unlikely to be considered sustainable, regardless of its other attributes.

Notably, several other sustainability dimensions tracked closely with “usefulness”, offering additional insight into how stakeholders distinguish between products that are simply functional versus those worth pursuing. Dimensions such as “superior to alternatives”, “responsible”, “ethical”, and “contributes to a collective good” followed nearly identical response patterns, with nano products ranking highest and GE products lagging behind. The nano-based flu vaccine emerged as the top-rated product across all five of these dimensions, with 80–90% of stakeholders selecting positive responses. Conversely, the genetically engineered mustard greens consistently received the lowest scores in this cluster, with positive ratings falling between 45% and 70%. These findings suggest that stakeholders may use “usefulness” as an initial practical measure but base their broader sustainability judgments on whether a product offers tangible improvements over existing options, upholds ethical standards, and contributes positively to society. Products perceived to meet these combined expectations—particularly the nanovaccine—are seen as not only viable but desirable innovations worthy of investment and continued development.

More broadly, our results echo a pattern in stakeholder preferences between nano- and GE-enabled products, with nano-based products generally perceived as more sustainable than their GE counterparts. When the sustainability sentiments for the six products were compared, the nano-enabled fruit coating and avian influenza vaccine received the most favorable ratings, followed by the phosphorus nano-fertilizer. In contrast, the genetically engineered mustard greens, beef cattle, and salmon were rated lower across most dimensions, with the mustard greens case receiving the lowest overall sustainability scores. These findings suggest that stakeholders distinguish between the two technology categories, not merely in technical terms but in relation to broader ethical, environmental, and societal considerations. Prior studies have also shown that consumers are more willing to purchase nano-enabled food products for multiple benefits than GE food products [62–64].

There are several possible explanations for the more favorable perception of nano. One contributing factor may be that nano applications, particularly those used in materials science and medicine—have been under development for several decades, leading to greater familiarity, more extensive safety evaluations, and more clearly articulated public benefits. However, GE foods have been in the market since the mid-1990s, albeit knowledge of their existence among consumers was low in earlier decades. The difference between nano and GE is mirrored in previous studies of consumer attitudes: research shows that while consumers express concern over both technologies, they are generally more averse to GE food products than to those containing nanomaterials. For instance, consumers are more likely to support labeling requirements for GE foods than for nano-enabled foods [62] and are often willing to pay more to avoid GE foods compared to nano-based alternatives [63,64]. Scholars have suggested that this divergence may be shaped by value-based predispositions—such as aversion to tampering with genes, preference for natural foods, or deeper associations between genetic modification and "unnaturalness"—in contrast to the perceived familiarity of chemical or material-based interventions in food [99]. They have also attributed past public controversies to GE foods and polarization surrounding them as factors in lower opinions of GE than nano [100]. These findings align with our results and suggest that perceived sustainability is shaped not only by technical or functional attributes, but by the cultural meanings, histories, and ethical associations that stakeholders bring to each technology.

The findings from this study offer actionable insights for innovation governance and policy development in agrifoods. Stakeholder assessments revealed clear distinctions not only between GE and nano-based products, but also among individual products within each category—highlighting that perceptions of sustainability are shaped by more than technical performance. Dimensions such as responsibility, equity, and contribution to the public good were central to stakeholder evaluations, underscoring the need for governance strategies that are nuanced and context-specific rather than guided solely by technology type. A one-size-fits-all regulatory approach may overlook important ethical and societal factors, whereas product-level evaluation informed by stakeholder input can support more responsible and widely accepted innovation pathways.

Nano-based products—particularly the nano-enabled avian influenza vaccine—emerged as strong candidates for future development. The nanovaccine received overwhelmingly positive ratings across multiple sustainability dimensions, including usefulness, ethicality, and contribution to a collective good, suggesting both high functionality and social value. However, while perceived as promising, some stakeholders also flagged barriers to commercialization, such as limited private-sector incentives and infrastructure readiness as well as expensive and uncertain regulatory hurdles. One stakeholder suggested that regulators should, "Allow for innovative, case-by-case flexibility in data requirements and assessments, [e.g.,] if a product is well understood and has numerous precedents with low risk—then find ways to expedite approval and minimize cost. Conversely do the opposite with products that pose potentially high uncertainty and risk. Rigid box-checking hurts all parties". These insights point to the need for proactive policy tools—such as targeted subsidies, public–private partnerships, or R&D investments focused on deployment—to help overcome market hurdles and bring high-value technologies to scale.

Crucially, our study also demonstrates the importance of incorporating stakeholder-informed sustainability assessments earlier and more systematically into the innovation pipeline. Traditional governance frameworks often emphasize risk assessment and regulatory compliance at later stages, typically after a product is nearing commercialization. However, such downstream evaluations may be too late to meaningfully influence product design or address public concerns before they solidify. By engaging stakeholders during earlier stages, especially between technology readiness levels (TRLs) 3 and 6, when product designs remain adaptable, developers can identify and respond to ethical, social, and practical concerns while there is still opportunity to refine the innovation trajectory. Researchers have argued that integrating ethical, legal, and social implication (ELSIs) assessments alongside traditional TRLs can enhance the legitimacy and viability of novel biotechnologies by surfacing concerns before they become barriers. For example, Trump et al. suggest evaluating ELSI concerns early in basic research stages in addition to assessing whether prototypes at more advanced research stages align with safety, security, and ethical expectations [101].

As with any expert elicitation study, several limitations should be acknowledged. First, while our sample of 42 U.S.-based stakeholders is comparable in size to similar studies in the literature, the modest sample limits the generalizability of the findings. We sought to ensure balance across stakeholder sectors, but representation from the government sector was notably lower, and the participant pool overall skewed toward individuals actively engaged in or supportive of biotechnology, potentially underrepresenting more critical or skeptical voices. While the generalization of findings may be more limited, transferability of qualitative results diminish the effect of this limitation by contextualizing individual stakeholder sentiments within repeatedly found concepts throughout the data. Second, the study focused exclusively on U.S. stakeholders to better inform U.S. policy; sustainability perceptions may differ significantly in other national or cultural contexts, and future cross-country comparisons could produce different, valuable results. Future studies should also consider the everyday immediate and adjacent consumers of products in stakeholder perceptions. Third, although the six case studies were carefully selected to reflect diversity across domains (e.g., environmental, human health, and animal applications), different case choices—particularly those perceived as highly controversial or unsustainable—could have led to different patterns of response. Further, our sample of stakeholders was more representative of plant biotechnology and agricultural systems expertise, with limited representation from individuals specializing in animal biotechnology or gene editing, despite three of the six case studies focusing on animal applications. However, we believe that the results of our data constitute a meaningful addition to the literature regardless of chosen products as each case study elicited both new and repeated results that contribute towards saturation of information related to more balanced products. Additionally, we focused our analysis on only one component of the engagement platform (Activity 3), meaning other potentially relevant data sources, such as participant characteristics and perspectives on science and technology gathered in other components, were not included here but may offer important explanatory context for future analyses. Despite these limitations, the study offers valuable insights into how a diverse set of stakeholders evaluates emerging food and agricultural technologies and provides a replicable framework for integrating sustainability considerations into technology governance.

The ten sustainability dimensions evaluated in this study also offer a novel theoretical and methodological framework for advancing sustainability assessment in emerging agri-food technologies and other fields. Theoretically, the multidimensional approach moves beyond conventional three-pillar models of sustainability by systematically incorporating additional ethical, social, and justice-based considerations that stakeholders actively apply when evaluating new technologies. Methodologically, the framework operationalizes these dimensions in a structured, stakeholder-centered evaluation platform that enables a more granular and holistic understanding of how diverse technologies are perceived across multiple domains of sustainability. While dimensions such as usefulness or technical efficacy elicited broad agreement, others revealed important divergence in stakeholder priorities and expectations, demonstrating the value of capturing multidimensional perspectives rather than relying on any single metric of sustainability. For example, while the gene-edited mustard greens were viewed as useful, they received lower ratings on environmental sustainability and equity, highlighting areas where further engagement or development may be needed to strengthen their sustainability profile. In contrast, the nanovaccine was broadly supported across both technical and normative dimensions, suggesting a clearer pathway for responsible advancement. Recognizing these differentiated patterns early in the innovation process allows policymakers, funders, and developers to better align product development with societal values, allocate resources more effectively, and design governance approaches that are responsive to stakeholder concerns. By embedding this multidimensional stakeholder evaluation framework into earlier phases of the innovation pipeline, the study demonstrates how sustainability can serve not only as an aspirational goal, but also as a practical, actionable tool for guiding technology design, governance, and investment decisions in ways that enhance legitimacy, trust, and societal benefit.

Finally, our findings carry broader implications for the future of sustainable agrifood innovation. If left unexamined, technological development risks becoming a narrow exercise in engineering efficiency rather than a collective project grounded in shared values. But the results of this study offer a more optimistic vision. They suggest that it is possible to design, assess, and govern technologies in ways that are not only technically effective but also socially legitimate and ethically informed. Whether that future becomes utopian or dystopian depends on our willingness to prioritize inclusive and anticipatory approaches to innovation. The tools to build a sustainable food system already exist—what remains is to ensure they are guided by the perspectives and priorities of the people they are intended to serve. As a next step, we feel that researchers should examine differences in stakeholder perceptions across sectors and disciplines, and how these perceptions evolve through structured dialog and deliberation. By exploring how conversations shape evaluations, we hope to deepen understanding of consensus, conflict, and learning within stakeholder communities. We also invite other researchers to adopt, adapt, and build upon this framework in future studies. The field urgently needs more transdisciplinary, stakeholder-engaged research to ensure that sustainability is not merely a label applied after the fact—but a guiding principle embedded at every stage of technological innovation.

6. Conclusions

This study provides the first systematic, multidimensional analysis of how U.S.-based expert stakeholders evaluate the sustainability of GE and nano-based products in agri-foods. By using real-world case studies and assessing them across ten key sustainability dimensions—environmentally sustainable, economically sustainable, socially sustainable, responsible, useful, superior to alternatives, ethical, fosters a fair and just society, contributes to a collective good, and equitable—we captured nuanced insights into how these emerging technologies are understood and judged by those with influence over their development, regulation, and adoption. Overall, nano-based products were viewed more favorably than their GE counterparts, with the nano-enabled flu vaccine and fruit coating receiving the highest ratings across multiple categories. At the same time, the GE mustard greens emerged as the least favored, raising questions about the types of benefits that are most valued when sustainability is at stake.

Notably, stakeholders evaluated sustainability holistically, tending to rate products consistently across dimensions. However, subtle variations in their responses reveal important distinctions that can inform more targeted and responsive innovation strategies. These findings underscore the value of multidimensional frameworks for sustainability assessment. Further, by capturing expert judgments on real-world products, our stakeholder engagement approach can help researchers, developers, and policymakers better anticipate which innovations are seen as both impactful and legitimate. Future work can extend this framework across additional products, sectors, and national contexts to build more responsive and inclusive strategies for sustainable agrifood innovation.

Supplementary Materials: The supplementary information file referenced in the text can be downloaded at: https://www.mdpi.com/article/10.3390/su17156795/s1.

Author Contributions: Conceptualization, M.D.H., C.L.C., J.K., K.D.G.; Methodology, M.D.H., C.L.C., K.D.G.; Software, M.D.H., C.L.; Validation, C.L.C., J.K., M.D., K.D.G.; Formal Analysis, M.D.H., C.L.C., C.L., K.D.G.; Investigation, M.D.H., C.L.C., J.K., M.D., I.C., M.C., C.L., N.L., K.D.G.; Resources, M.D.H., C.L.C., J.K., M.D., M.C., N.L., K.D.G.; Data Curation, M.D.H., C.L.; Writing—Original Draft Preparation, M.D.H., C.L.C., J.K., M.D., I.C., M.C., C.L., N.L., K.D.G.; Writing—Review and Editing, M.D.H., C.L.C., J.K., M.D., I.C., M.C., C.L., N.L., K.D.G.; Visualization, M.D.H.; Supervision, C.L.C., M.D., K.D.G.; Project Administration, K.D.G.; Funding Acquisition, K.D.G., J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Social Implications of Food and Agriculture Technologies Program Area, A1652, project award no. 2022-67023-36730, from the U.S. Department of Agriculture's National Institute of Food and Agriculture. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

Institutional Review Board Statement: The research protocol was reviewed by the Institutional Review Boards of North Carolina State University (IRB ID # 26701, date 2023-12-15) and Iowa State University (IRB ID 24-038, date 2024-03-01), both of which determined the research to be exempt from further ethical review.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets presented in this article are not readily available because they are part of an ongoing study. Requests to access the datasets should be directed to the corresponding author.

Acknowledgments: The authors would like to thank Sharon Stauffer for her invaluable support in coordinating the engagement activities, as well as all of the participants who completed our study and provided valuable feedback.

Conflicts of Interest: The authors declare no conflicts of interest.

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