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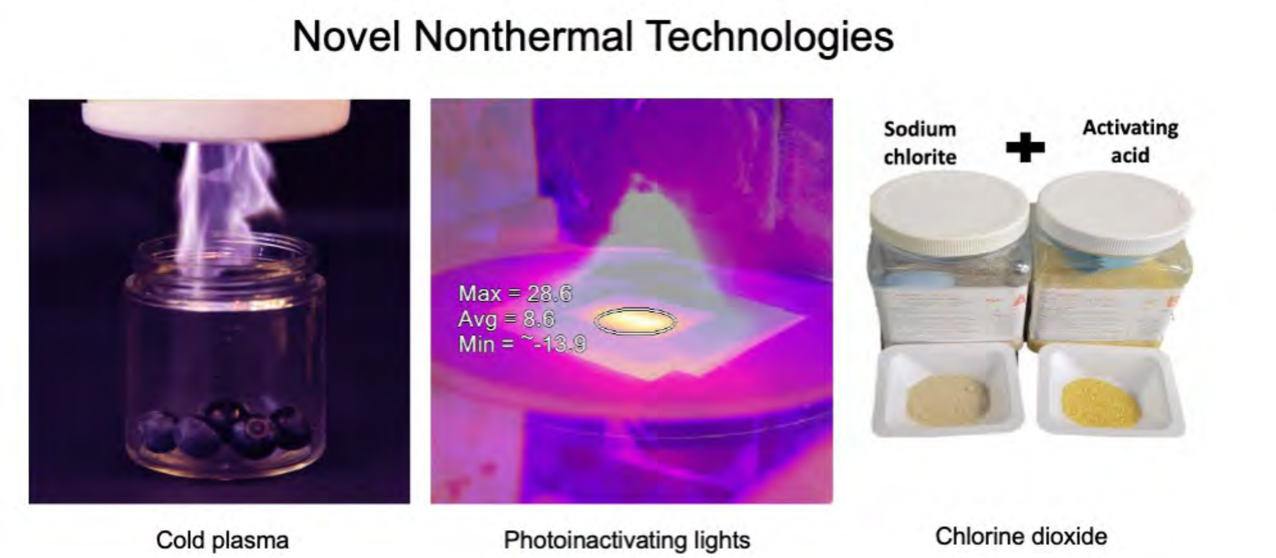

Facilitators and Barriers to the Implementation of Waterless Nonthermal Technologies to Enhance Food Safety in the Produce Industry

ABSTRACT

Nonthermal technologies offer important solutions to urgent food safety problems. Our project team researched and developed three technologies, cold plasma, photoinactivating lights, and gaseous chlorine dioxide (ClO_2), as potential solutions to the industry's ongoing food safety concerns. In 2022, the research team hosted an annual stakeholder meeting to receive feedback on the technology developed and assess facilitators and barriers to implementation. The meeting took place virtually using Zoom; three technology-specific presentations and one outreach-focused presentation were delivered. Participants were divided into pre-assigned breakout rooms after a brief opportunity for questions and answers. Breakout sessions were recorded, transcribed, and edited for clarity by two independent coders. The transcripts revealed several themes about the adaptability of the technology, the cost of implementation, the knowledge base of stakeholders, and regulatory issues. Technology adaptability was the most significant theme throughout the sessions, revealing no one-size-fits-all solution to food safety. Cold plasma and ClO_2 had the most mentions of adaptability, which showed the multiple use cases for the technologies. More importantly, for these technologies to have the best outcome in improving food safety, a diverse population of stakeholders needs to be engaged.

INTRODUCTION

The requirement for safe and unadulterated food products has driven the exploration of innovative food processing technologies that do not compromise quality or cost. Traditional methods of steaming, roasting, sanitizing with chemicals, and canning achieve pathogen reduction and food preservation, altering the organoleptic or sensory characteristics of food products *(8)*. Nonthermal technologies are methods of preserving food that do not rely on heat or large quantities of water to kill microorganisms or inactivate enzymes *(5)*. Several nonthermal technologies have emerged as promising methods to address food safety challenges in the produce and low-moisture food industry. These technologies can potentially reduce alterations in sensory characteristics and the detrimental effects of heating or excess moisture.

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Nonthermal technologies offer important solutions to urgent food safety problems. Several commodities, such as low-moisture foods, fruits, and leafy greens, deal with persistent biological hazards throughout the production continuum *(5)*. In addition, many of these commodities have stringent metrics for temperature, relative humidity, water activity, and moisture content to meet quality standards *(5)*. Traditional disinfection methods involve washing with a sanitizing chemical or applying heat, which may not be suitable for all commodities, leaving food safety gaps. These gaps can be filled by implementing novel nonthermal technologies. However, before being implemented commercially, more information about a new technology's potential value is needed.

Our project team researched, identified, and developed three technologies–cold plasma, photo-inactivating lights, and gaseous chlorine dioxide (ClO_2)–as potential solutions to the industry's ongoing food safety concerns *(3, 6, 7, 9, 11)*. Cold plasma is a technology that uses ionized gases to kill microorganisms on food surfaces *(8)*. This antimicrobial intervention offers the advantage of being chemical- and water-free, in addition to being able to operate openly and continuously at atmospheric pressure *(8)*. Cold plasma has been employed for bio-decontamination and sterilization of surfaces, medical instruments, water, air, food, and living tissues without causing damage *(8)*. Gaseous ClO_2 is a dry treatment with the ability to penetrate complex surfaces and treat food products without affecting their quality *(4)*. It can be applied as a fumigant using a dry precursor method, allowing for convenient usage and cost efficiency by using less storage space, water, and electricity *(10)*. Photo-inactivating lights have many food safety applications, such as surface disinfection, water treatments, and air purification. Using light technology provides the benefit of no chemical input and does not inherently require any water.

The adaptation of novel technologies requires immense upfront capital investment and updated regulatory oversight in addition to sound scientific data on efficacy. In addition, regulatory hurdles are costly to meet and time-consuming to navigate. Taken together, many promising technologies do not make it out of the development stage. Many of these advancements, photoinactivating lights, cold plasma, and gaseous ClO_2 are still in their nascent stages of development for the food industry, and proof of concept trials are often limited to the laboratory scale. In the field of technology transfer, there is a concept called the "valley of death," which describes the pitfalls between academic research and the commercialization of technology *(5)*. This gap occurs after researchers have developed a promising idea, received funding through grants, and then run out of resources to move the idea to the next stage. Ultimately, bridging this gap is critical and requires significant capital investment and time to move the product through the path to commercialization.

Facilitating the transfer of technologies from the laboratory to industry requires iterative communication between scientists at the academic and government levels and members of the industry. Researchers leading a USDA-funded project hosted a stakeholder meeting to present updates on their work and to facilitate a conversation between government researchers, academics, industry representatives, and scientific administrators. This meeting aimed to assess the barriers and facilitators to the industrial application of cold plasma, photoactivation lights, and gaseous ClO_2. In addition, the stakeholders were presented with results from a consumer outreach survey, attempting to gauge public opinion about each technology. From these conversations, "stakeholder-driven" research can be developed to avoid barriers before they become pitfalls to implementation.

MATERIALS AND METHODS

The Virginia Tech Institutional Review Board (VT IRB 22-261) determined this project did not meet the definition of human subject research. Therefore, no further approvals were needed.

Participant recruitment

Members of the research team hosted an annual project stakeholder meeting. Invitations to attend the 2022 meeting were sent via email to 200 individual researchers, academics, industry representatives, and scientific administrators six weeks before the meeting. These individuals were members or affiliated with the project's advisory board and were identified based on their professional expertise, leadership within the food processing industry, and previous engagement with the project. Reminders were sent one week before the event. The meeting took place virtually using Zoom (Zoom, San Jose, CA), and participants filled out a Zoom registration survey to receive the meeting link. One component of the registration survey allowed was for participants to identify their stakeholder group: food industry (4 individuals from separate companies), scientific administration (3 individuals representing three commodity leaders), government research (4 individuals from the federal government), or academia (4 individuals from two universities). This was done to identify the participant's expertise, perspectives on food safety issues, and any biases or preconceived notions of the technology. The stakeholders were assigned to one of four breakout sessions based on the group they self-identified into to help achieve a consensus opinion within that group. Participants were informed that breakout sessions would follow presentations and be recorded, and consent was implied by submitting their registration.

Meeting structure

The meeting took place in April of 2022 and lasted approximately six hours, with variable breaks between sessions. The meeting began with everyone in attendance introducing themselves, followed by three technology-specific presentations and one presentation focused on the outreach portion of the project. The presentations were an opportunity for the project team to provide background information and updates on their portion of the research. Following a brief opportunity for questions and answers, participants were divided into their previously assigned to one of five breakout rooms. Each breakout room was hosted by a facilitator who utilized a semi-structured focus group script (supplementary data) to lead the discussion based on the previous presentation. This allowed each breakout group to be asked a common set of questions and the flexibility for the facilitator to ask follow-up questions as appropriate. Each breakout session started with a reminder from the facilitator that the sessions would be recorded and that the data would be used in the development of presentations and papers. All breakout sessions were recorded using Zoom, and breakout recordings were uploaded to a shared cloud folder for storage.

Meeting transcript analysis

Meeting recordings were uploaded to Otter.ai (Mountain View, CA) for full transcription and further edited for clarity. Before the analysis, the coders reviewed notes from previous stakeholder meetings to identify deductive codes, categories, and themes and used them to analyze codes from the transcripts *(Table 1)*. The transcripts were reviewed independently by two coders. The coders utilized a consensus model to find agreement on how segments of text from the transcripts were coded, categorized, and thematically grouped. If there was disagreement between the coders, that segment was discussed until a consensus was reached. This process repeated itself for each transcript, and the complete dataset was checked for agreement.

RESULTS

The results presented here represent the transcripts that were successfully recorded, transcribed, and analyzed. Due to a technical error, one of the recordings was not usable.

Recruitment, enrollment, and retention of participants

Approximately 200 invitations were sent out to stakeholders, and of that, 40 people responded. On the day of the event, 15 people logged into Zoom and were assigned to breakout sessions. The participants were allowed to come and leave the meeting as their schedule allowed, and participation decreased to approximately 12 by the end of the meeting. As participants decreased, breakout sessions were combined to ensure at least three people in each group.

Overarching themes

Once final transcript data were compiled, it was analyzed for overarching themes and categorized as either a facilitator or barrier to the technology's implementation and adoption in a commercial setting. The transcripts revealed several themes mostly generalized to the adaptability/scalability of the technology, the impacts of cost on implementation, the existing knowledge base of stakeholders or misconceptions, and how the technology would be regulated on a local, state, and federal level *(Table 1)*.

Adaptability was considered a feature of a technology or a process that can change with unexpected environmental disturbances and be seamlessly introduced into an existing process. The general adaptability of technology was considered a facilitator of implementation, whereas issues with regard to scalability were considered a barrier *(Table 1)*. Overall, the adaptability of the technologies was the most commented on. Adaptability was discussed 20 times concerning cold plasma, while scalability issues were mentioned 23 times. The industry group made no mentions of adaptability for cold plasma, which my reflect the need for more education about the technology for this group. For ClO_2, adaptability was mentioned 20 times, and scalability issues were brought up three times. Photoinactivating lights had 13 mentions of adaptability and 33 mentions of scalability issues. It was noted that the scientific administration group alone had a combined 33 mentions of scalability issues for all technologies. In comparison, the government, industry, and academic groups had a combined 26 mentions of scalability issues for all technologies.

Education was defined as knowledge of the technology, and misconception was defined as a lack of knowledge of the technology. The transcripts reflect more misconceptions than a robust knowledge base for each nonthermal technology. Cold plasma had 24 mentions of misconceptions, which was the highest out of all the technologies presented, and no mention of an educational base. Photoinactivating lights had the most mentions of an educational knowledge base, with six mentions of education and six mentions of misconceptions. Chlorine dioxide had four mentions of education and five mentions of misconceptions. The industry group had the most mentions of misconceptions, followed by government, administration, and academia.

Regulation was a major theme discussed in each breakout group and for each technology. The mention of regulation was coded to reflect the regulatory agencies, at local, state, federal, and global levels, who need to assess the safety and efficacy of new technologies. Cold plasma and photoinactivating had the most mentions of regulation, with 12, and ClO_2 had six mentions of regulation. The most mentions of regulation came from administration and industry stakeholders.

The cost came up in each of the technology-focused breakout sessions as a barrier to their continued development and implementation. The cost was considered a barrier to scaling up due to a lack of capital investment or perceived value added. Photoinactiviating lights had the most mentioned cost, with seven, followed by cold plasma and ClO_2. Cost was mentioned equally amongst all the stakeholder groups and was the topic least discussed.

TABLE 1. Summary of the total mentions of the barriers and facilitators to implementation for cold plasma, photoinactivating lights, and gaseous chlorine dioxide. The mentions were coded based on a consensus model with two independent coders reviewing transcripts created from four breakout groups discussing each technology. NA represents recordings that were lost due to technical errors

	Cold Plasma Facilitators (mentions)	Barriers (mentions)	Photoactiving Light Facilitators (mentions)	Barriers (mentions)	Chlorine Dioxide Facilitators (mentions)	Barriers (mentions)
Academic	Adaptability: 7	Cost: 2 Regulation: 3 Misconceptions: 2 Scalability: 4	Adaptability: 2 Education: 3	Cost: 3 Regulation: 0 Misconceptions: 0 Scalability: 4	Adaptability: 3 Education: 2	Cost: 1 Regulation: 1 Misconceptions: 2 Scalability: 0
Industry	Adaptability: 0	Cost: -- Regulation: 1 Misconceptions: 7 Scalability: 2	Adaptability: 7 Education: 3	Cost: 2 Regulation: 9 Misconceptions: 5 Scalability: 2	Adaptability: 10	Cost: 1 Regulation: 2 Misconceptions: 1 Scalability: 0
Government	Adaptability: 11	Cost: 1 Regulation: 2 Misconceptions: 9 Scalability: 7	Adaptability: 4	Cost: 2 Regulation: 2 Misconceptions: 0 Scalability: 7	Adaptability: NA	Cost: NA Regulation: NA Misconceptions: NA Scalability: NA
Administration	Adaptability: 2	Cost: 2 Regulation: 6 Misconceptions: 4 Scalability: 10	Adaptability: --	Cost: -- Regulation: 1 Misconceptions:1 Scalability: 20	Adaptability: 7 Education: 2	Cost: 1 Regulation: 3 Misconceptions: 2 Scalability: 3

DISCUSSION

This meeting revealed the importance of stakeholder engagement while developing new technologies. By communicating with stakeholders about the benefits and limitations of technology before major capital investments are committed, major pitfalls can be avoided. In addition, any regulatory hurdles or safety concerns can be addressed before taking laboratory findings and applying them at a commercial scale.

Cold Plasma

Cold plasma is an emerging nonthermal technology that decontaminates the surfaces of fresh produce and has the most mention of adaptability. One example of cold plasma's adaptability was described by a stakeholder "[y]ou don't have to have any sanitizing chemicals as part of this… you don't have any trucks that are pulling up with loads of concentrated chemicals. So, you don't have all the manufacturing costs of producing those chemicals." However, further optimization is necessary to control temperature and potential damage to the treated product while achieving the food safety need. For cold plasma, one participant identified that "[i]t needs to be tuned every time. So that's one of the advantages of plasma is it is highly tunable. One of the disadvantages is it needs to be tuned." This quote illustrates the paradox of adaptability by stating that multiple parameters still need to be optimized even when technology has a lot of flexibility. Cold plasma may facilitate the production of high-quality food and enhance food safety, but it still requires innovation to be applied at a commercial scale. Since cold plasma does not require water as an input it can be implemented into dry sanitation. One stakeholder from the industry noted, "I'm encouraged about the dry sanitation part …because that's the challenging part in the sanitation plan."

As novel antimicrobial technologies emerge, regulatory agencies need to assess their safety and efficacy. Stakeholders were concerned that cold plasma has no clear regulatory path forward *(11)*. One participant asked, "So how do we go through regulatory? Do we need to be regulated on a per-produce basis? Or do we need to be regulated …the way radiation is regulated?" Since cold plasma can generate a combination of many antimicrobials, such as UV light, ozone, and radical oxygen species, it is difficult to categorize given the current food regulations practiced in the United States *(11)*. Depending on how it is applied, cold plasma technology could be considered a food additive or a food-contact substance. If a manufacturer intends to use cold plasma as a food additive, they need to provide safety data to the FDA to demonstrate its effectiveness and safety *(11)*. Since demonstrating safety and efficacy is costly and time-consuming, the industry would likely need to form a consortium to demonstrate its value to consumers and the FDA.

Cold plasma may facilitate the production of high-quality food and enhance food safety, but it still requires innovation to be applied at a commercial scale. Cold plasma is generated with a basic principle involving energizing a neutral gas system *(10)*. However, this technology is relatively novel and not well understood, with one participant sharing, "[i] t's too new. It's too strange… it just looks too crazy." Consequently, it requires the use of high-voltage electricity, which can bring up some safety issues, such as when one participant asked, "You know, you've got all this high-voltage electricity. I mean, is this equipment dangerous? And my answer is that is always, well, yeah, it's dangerous. It's high voltage electricity. You know, in the same way, that … you've got a lot of knives and crushers and choppers." This quote highlights that cold plasma, like any industrial equipment, worker safety, and training will be critical to its adoption into commercial settings.

Photoinactivating lights

Photoinactivating lights, especially ultraviolet (UV) light, have a long history of use in the food industry. UV light is considered a viable food safety additive on foods and food contact surfaces as a surface antimicrobial under the code of federal regulation *(17)*. The advantage of UV light's regulatory status was mentioned by a stakeholder when "[c] ompared to cold plasma, UV light -– is this not unfamiliar to the industry as well as to the consumers.? It is better position[ed] compared to cold plasma." However, there was significant discussion, especially in the industry breakout session, about the ability to make a pathogen reduction claim about UV light treatment. Photoinactivating light technology is different from chemical sanitizers which have EPA label claims for a specific reduction of pathogens. One industry stakeholder noted "You don't have a definition for if I treat my produce at the packing house... "Is that two log reductions in *Salmonella*? Who knows? What's the measure of success that everybody's looking for?" A recent compliance advisory stated, "EPA cannot confirm whether, or under what circumstances, UV light devices might be effective against any pest, including viruses and bacteria" *(17)*. The lack of a targeted benchmark for pathogen reduction is a big concern for food processors that wish to demonstrate to regulators that their food safety program is hitting their recommended target for pathogen elimination.

Photoinactivating light technology does not rely on chemicals for sanitation; instead, it has the ability to penetrate through the material to reach the target pathogen. Throughout the breakout sessions, issues of scalability around the use of light technology in an agricultural or food-processing setting were mentioned. The scientific administration group had the most concern with the scalability of photoinactivating lights, mostly citing difficulties applying it to pre- and post-harvest water. For example, UV light is utilized as a sanitizer by the food and beverage industry for sugary syrups and liquid sweeteners because they can be a breeding ground for pathogens *(7)*. However, not all liquids can easily be treated, especially if there is high turbidity and debris in the water that prevents the light from penetrating and reaching the target microorganism. One stakeholder noted" "[i]f you go out into the field and watch a working dump tank, over the course of a day's job of washing … that stuff looks like mud at the end of the day." This quote highlighted stakeholders' concern when conditions for light technologies are not ideal and debris in the water prevents the light from reaching its target pathogen.

While photoinactivating lights have been used in the industry for decades, several technological advances have made their application novel *(7)*. For example, new wavelengths in the far UV and visible light spectrum (405 nm) have emerged in the field of medicine for surface decontamination. They can be applied to foods and food contact surfaces *(3)*. In addition, the photoinactivating light industry has been able to lower cost barriers and safety because "there's been a lot of development in new LED UV sources there, UVB and even UVA." There were several mentions in the industry of emerging data about novel wavelengths of antimicrobial lights that gained the attention of many food processors and engineers. However, for these emerging light technologies to be successfully utilized by the industry, more scientific data and a demonstration of efficacy at a commercial scale are needed.

Chlorine dioxide

Chlorine dioxide has a long history of use in the produce industry as an antimicrobial agent and biocide *(13, 14)*. Most ClO_2 applications are in the aqueous form for pre- and post-harvest water disinfection. In recent years, gaseous ClO_2 has demonstrated efficacy in removing pathogens from the surface of produce *(6)*. Gaseous ClO_2 treatments on produce have been successful during long-term storage when dry conditions are needed *(6)*. Chlorine dioxide had 20 mentions of adaptability throughout the breakout session, reflecting its ability to be successfully implemented in food processing. One industry stakeholder highlighted the potential of gaseous ClO_2: "It's more like a biostat, you're not reducing a lot of molds, you're not killing a lot of molds, but you're keeping a lot of organisms from blossoming and out competing for the natural microflora." The value of using

ClO_2 as a biostat is that it allows for significant shelf-life extension with minimal product usage, and it reduces the risk of the accumulation of chemical residues. During the breakout session, a scientific administrator commented that "[i]t was compelling to have the gaseous solution. And my second takeaway was, h]ow great to get a three-for-one benefit of produce safety from pathogens, produce safety from aflatoxin. And combined with that, the risk factor of reducing navel orange worm." This quote highlights the need for adaptable food safety technologies to serve more than one purpose by mitigating multiple risks factors and hazards.

For gaseous ClO_2 to be integrated into post-harvest produce operations, more education about the technology is needed. Most stakeholders, when presented with information on gaseous ClO_2, thought of the aqueous water treatments and "not so much treating the surface of produce." Chlorine products like sodium hypochlorite (NaOCl) are used in high volume in the produce industry to treat water and prevent cross-contamination. However, NaOCl's efficacy against pathogens is limited and can be heavily impacted by pH, organic matter and turbidity *(7)*. Both aqueous and gaseous ClO_2 are alternatives to NaOCl-based sanitizers used in surface decontamination, prevention of cross-contamination safety, and shelf-life extension. Unlike NaOCl, ClO_2 is not impacted by organic material and is efficacious over a wide range of pHs *(7)*. However, stakeholders require more education about the value added by both aqueous and gaseous ClO_2. Specific information is needed on the additional cost, the potential value-added, and the mitigation of food safety risks of sanitizers like ClO_2.

Both gaseous and aqueous ClO_2 are used in the food industry and are regulated separately. For aqueous ClO_2, the FDA has set a residue limit of 3 ppm residual according to Title 21 CFR Part 173, which provides specifications for its use in food processing (13). However, ClO_2 in its gaseous form has more ambiguous regulatory oversight *(16)*. Currently, gaseous ClO_2 is regulated by the EPA as an antimicrobial pesticide because it is typically applied as a fumigant on raw commodities such as potatoes and grain. Currently, the only produce that has EPA-approved safety and efficacy data for is tomatoes and cantaloupe *(4)*. During the breakout session, one participant shared that regulatory expansion is progressing and that "[w] e're expecting a new label (EPA) with ten crop groups. And this will greatly expand the interest ..." the will allow for gaseous ClO_2 to be applied to all crop groups. The expansion of the EPA labeling will increase the adaptability of this technology by removing an important regulatory hurdle.

Outreach

Changes in food trends, climate change, or the increase in consumer empowerment in decision-making allow new technologies to have an increasing impact on food processing *(1)*. Scientific research is often perceived as detached from the public interest and lacking the reciprocal relationship between scientists, policymakers, and the greater public. Throughout the day, participants expressed their appreciation for the opportunity to express their opinion on a given technology and that the meeting served as "a great reminder that science data and facts will get you so far." A significant facilitator to outreach and education discussed throughout the day included the Cooperative Extension system and its ability to bridge gaps between research, application and consumers. Participants described some of the barriers to education and outreach included limited capacity of educators, the role of federal agencies in educating consumers and the role of the food industry as co-educators, educating future food science professionals on how to communicate their science to the general public, and combatting misinformation about food processing and technologies.

For education and outreach to be effective, there needs to be a meaningful level of engagement between the disseminators of information and the recipients of new knowledge. While Cooperative Extension educators can be valued partners in this education and outreach, recent research has documented they experienced an overall feeling of "being spread thin" among educators *(1)*. Cooperative Extension educators are increasingly required to take on multiple responsibilities to support stakeholders in pursuit of meeting benchmarks *(1)*. To minimize costs, fewer educators are responsible for covering larger areas or geographic regions *(1)*. Consequently, educators expressed concerns about multiple responsibilities and managing content outside their area of expertise. During one of the industry breakout sessions, the discussion centered on the lack of company resources to educate the public on their novel technologies. One participant shared that "as a taxpayer, I think it is the responsibility of USDA to manage that education if that makes any sense. Because we don't, I don't, have enough money to educate." This illustrates the strain that educating consumers can have on the food industry trying to innovate in a competitive marketplace when the marketing budget around the technology is unavailable.

There also needs to be a focus on educating the public about consuming processed foods using these technologies. This role could be met through partnering with Cooperative Extension educators, who specialize in translating technical data into accessible, actionable information for any given audience. In the present study, as part of the overall project, scientists were encouraged to present the research in new and engaging ways, such as short videos, to facilitate engagement. Some contributors to the content presented in the meeting were graduate students, postdoctoral fellows, and early career scientists who may feel trepidation engaging in activities outside the laboratory. However, engaging in scientific outreach through stakeholder meetings provides opportunities for young scientists to develop translatable skills, facilitating adaptive communication, critical thinking, networking, and leadership.

Participants suggested that interactive conversations are important for early technology adoption – opening a dialogue about the technologies could create interest and buy-in from potential industry users and consumer acceptance. People may misunderstand information because of exposure to inaccurate facts, faulty reasoning, or misinterpreting material they read, hear, or observe. They may have preconceived notions about something that would need to be overcome through education. In the case of many technologies, education will need to focus on training industry users. It may require highly trained technical staff to maintain the equipment and ensure food safety specifications are being met.

CONCLUSION

Overall, novel antimicrobial technologies offer a promising avenue for enhancing food safety regulation by providing innovative tools to prevent, detect, and control microbial contamination in the food supply chain. As these technologies continue to evolve, collaboration between regulatory agencies, industry stakeholders, and scientific researchers will be essential to ensure their effective integration into food safety practices. Bridging the gap to commercialization not only requires engineering expertise but also continuous engagement with the target industry *(5)*. This is because there is no one-size-fits-all remedy for food safety since each commodity has specific needs.

Over the years, several improvements and innovations in nonthermal technologies have been realized. The challenge of adapting to accelerated changes in the food processing environment requires a continuous innovative approach from the food industry. Throughout breakout sessions, investigators were encouraged to find a "star" commodity ready for a technological advance and research each step of the commercial process. Future meetings will continue to engage diverse stakeholders to facilitate the best possible food safety and quality outcomes.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

Generative AI was not used in the fabrication of this manuscript. Any AI-assisted technology was applied to improve the readability of the manuscript.

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