CENTER for PRODUCE SAFETY

# CPS 2021 RFP
# FINAL PROJECT REPORT

## Project Title
Practical application of superheated steam to harvesting, processing, and produce packing tools and equipment

## Project Period
January 1, 2022 – December 31, 2023


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## Objectives

1. *Develop a model for superheated steam (SHS) efficacy as a function of surface features and treatment parameters.*
2. *Quantify the change to ambient relative humidity as a consequence of the extended use of SHS in indoor spaces as a function of steam flow rate, duration of treatment, size of enclosure, room ventilation, and air handling system.*
3. *Develop key performance indicators around SHS efficacy, implementation costs, and safety standards for produce industry adoption of this novel technology.*


**Funding for this project was provided partly through the CPS Campaign for Research**

# FINAL REPORT

## Abstract

Sanitation in dry produce environments is challenging due to the exclusion of water. Superheated steam (SHS) is a novel sanitation technique that utilizes high temperature steam to inactivate microorganisms. Superheated steam represents an alternative to conventional dry sanitation strategies (physical removal and spot-cleaning with sanitizer, or intermittent wet cleaning, etc.) utilized in dry produce handling operations. However, the majority of the current work on SHS is limited to bench-scale treatments and neglects the scientific evaluation of other key attributes beyond microbial inactivation. Our research aimed to fill that gap by assessing the following:

*Superheated steam efficacy as a function of surface features and treatment parameters:* We evaluated the thermal surface inactivation of dried-down spot-inoculated *Enterococcus faecium* on stainless steel coupons (10.2 x 10.2 $cm^2$) during brief (2, 5, 10 s) stationary SHS exposures of 397°C (2.5 cm nozzle-surface distance and 23.5°C ambient temperature). Coupons were inoculated at three locations: geometric center, and at 2.3 and 4.6 cm from the geometric center. Superheated steam achieved the microbial reduction of $4.78 \pm 0.87$ log CFU/$cm^2$, $7.72 \pm 1.50$ log CFU/$cm^2$, and $9.60 \pm 0.13$ log CFU/$cm^2$ at the impingement point for 2, 5, and 10 s, respectively. At 2.3 and 4.6 cm from the geometric center, reduction was highest during 10 s at $5.11 \pm 1.87$ log CFU/$cm^2$ and $2.81 \pm 0.67$ log CFU/$cm^2$, respectively.

*Change to ambient relative humidity (RH) as a consequence of the extended use of superheated steam in indoor spaces:* SHS application did not significantly ($p > 0.05$) increase the ambient temperature nor RH among any of the tested indoor spaces. Notably, at the location immediately (0.3 m) in front of the SHS nozzle, a significant increase in RH ($p < 0.001$) and temperature ($p < 0.001$) was observed. The maximum increase in RH and temperature change were 47% (0.3 m distance from steam source, small facilities with high ventilation rate) and 9.3°C (0.3 m distance from steam source, large facilities with low ventilation rate), respectively, when examining all facility spaces over a 5 h treatment. Similarly, steam cooling and limited surface condensation occurred. The results suggest that prolonged SHS exposure did not substantially increase the RH or temperature of the processing environment.

*Efficacy and deformation of different surface materials:* Coupons made from test surfaces were treated by SHS at 150°C for 3 min. Treatment resulted in 10 $\log_{10}$ CFU reduction for most surface coupons except for cardboard (9 $\log_{10}$ CFU). Low hydrophobicity and high thermal inertia of surfaces appear to be correlated with microbial inactivation. Selected surfaces (stainless steel, plywood, and silicon rubber) were treated with SHS at 150°C for 5 min once per week for 4 weeks. After the treatment each week, we monitored the change in roughness and hydrophobicity (contact angle) of the treated surfaces. A slight increase in the hydrophobicity of silicone rubber and stainless steel but no significant change in roughness was noted.

*Employee safety:* The 29 CFR 1910 General Industry Code and General Duty Clause were identified as relevant requirements of the Occupational Safety and Health Administration regulations. Consequently, operators should don personal protective equipment including goggles, heat and waterproof gloves, and slip and impact-resistant, waterproof shoes. Employee safety training is needed to prevent accidents. To evaluate operators' perceptions of safety hazards, human subjects were presented with safety training and were then asked to operate a pilot-scale unit and provided feedback via survey. Before the trial, seven respondents found the technology "very dangerous" or "dangerous," with no respondents perceiving it as "safe." After the subjects used the pilot-scale unit, the number of subjects who viewed the tool as "not very dangerous" (n=8) and "safe" (n=2) increased, though this was not statistically significant.

Taken together, the findings from this research can help the industry balance tradeoffs with using superheated steam as a surface sanitizer.

## Background

Sanitation within dry environments is a challenge that has been recognized for over a decade. Dry processing facilities, such as dry produce handling operations, typically exclude traditional wet sanitation approaches to limit the introduction of water (FDA, 2018). Although there are conventional dry sanitation strategies, including alcohol-based sanitizers, product push through, gaseous ozone, and $CO_2$ blasting, these dry sanitation methods can result in limited microbial inactivation, potential chemical residues, operating hazards, and may be high cost.

Superheated steam, or "dry steam," is a novel alternative to sanitizing that uses limited water. Superheated steam can achieve high temperatures (125°C to >300°C) by heating saturated steam with additional sensible heat above the saturation point at a constant pressure (100°C at atmospheric pressure) (James et al., 1998; Park et al., 2021). In contrast to saturated steam, any decrease in temperature at a given processing pressure will not result in condensation since superheated steam has greater thermal energy and exceeds the saturation temperature (Park et al., 2021). Similarly, superheated steam can rapidly increase surface temperatures as a result of its increased heat transfer rate and has the ability to effectively penetrate cavities and crevices (Morgan et al., 1996a; Morgan et al., 1996b). Therefore, it could be effectively used in food and produce handling environments for elimination of target microorganisms. Previous bench-scale studies reported the efficacy of superheated steam treatments for rapid microbial inactivation of diverse targets within food matrices and food processing surfaces (e.g., stainless steel, polyvinyl chloride); however, this dry sanitization technology has not been examined on the commercial scale (Ban et al., 2014).

Superheated steam technologies could be applied within dry production spaces (e.g., conveyor belts in dry processing or produce packinghouses) where conventional wet sanitation is not feasible. However, it is imperative to examine varying parameters influencing the operational performance of commercial-scale units to better understand industrial outcomes (Ban et al., 2014). Our research provided a more comprehensive approach to evaluating superheated steam performance in dry produce operations to move the needle forward for commercial application.

## Research Methods and Results

*Objective 1: Develop a model for superheated steam (SHS) efficacy as a function of surface features and treatment parameters.*

*Methods:*

Superheated steam unit: To investigate the effect of coupon thickness on temperature distribution, 0.05 cm, 0.28 cm, and 0.48 cm thick stainless steel coupons (AISI 304, No. 2B polished finish, length x width: 30.5 x 30.5 cm) (Online Metals, Seattle, WA, USA) were used. Nine K-type, 0.05 cm diameter, thermocouples (SZZJ Inc., China) were placed on the target side of each coupon, as shown in **Fig. 1b**, and an 8-channel handheld data logger (OMEGA Engineering, Norwalk, CT, USA) was used to record the surface temperature. The stainless steel coupons were fixed in an upright position and the SHS nozzle was pointed at the geometric center of the coupons at a distance of 2.5, 5.1, or 7.6 cm from the coupon surface.

Bacterial inoculation: Stainless steel coupons (AISI 304, No. 2B polished finish, length x width x thickness: 10.2 x 10.2 x 0.05 cm) (Online Metals) were initially soaked in ethanol (70% EtOH) and wiped with paper towels, then airdried overnight. The coupons were then sterilized in an autoclave (Steris®, Mentor, OH, USA) at 121°C for 30 min under 15 psi. To simulate surface contamination scenarios from introduction of moisture (e.g., hydration event or wet sanitation regime) in a dry food processing setting, the coupons were spot inoculated (20 μL) with concentrated *Enterococcus faecium* NRRL B-2354 in an area of 1 $cm^2$ in the geometric center of the coupon. The coupons were air dried for 20 ± 4 h at room temperature in a biosafety cabinet (Thermo Fisher Scientific, Waltham, MA, USA) before thermal treatment. The average ambient temperature and relative humidity (RH) within the biosafety hood were 20.9°C ± 0.89 and 16.3% ± 1.89. The initial population of *E. faecium* at the inoculation site after conditioning was 9.60 ± 0.13 $log_{10}$ CFU/$cm^2$.

Human subjects: Human subjects (n=24) were recruited with digital advertisements (i.e., flyer and recruitment email) disseminated through the Cornell email listserv consisting of students, faculty, and staff. The safety procedures of the study and protocol for manual operation of the superheated steam unit were approved on February 6$^{th}$, 2023 by Cornell University's Instructional Review Board (IRB) for Human Participants (IRB0147190) prior to research intervention. Subjects were informed of the two-day commitment to attend the following components: a training presentation about the commercial-scale superheated steam unit (Bayzi Corporation, Cincinnati, OH, USA), experimental operation of the unit for microbial inactivation of dried-down spot-inoculated *E. faecium* on stainless steel coupons, and a brief survey. Subjects completed an IRB informed consent form prior to the study to acknowledge the purpose of the research, voluntary filming of the superheated steam application, confidentiality and deidentification, and voluntary participation within the study. Demographic information (i.e., age and gender identity) and prior professional experiences (i.e., food industry and/or food safety) were recorded from each subject via a paper survey.

*Results:*

We characterized the surface temperature gradient on stainless steel coupons (30.5 x 30.5 $cm^2$) outward from the impingement point (0, 2.3, 4.6 cm) during stationary superheated steam exposure at 397°C. The impact of coupon thickness (0.05, 0.28, 0.48 cm), ambient temperature (23.5, 12.8, 4°C), and distance between the steam nozzle and surface (2.5, 5.1, 7.6 cm) were evaluated. Surface temperatures exceeded 300°C at the impingement point but decreased as surface thickness, steam nozzle-surface distance, and distance on the surface from the point of impingement increased. Ambient temperature negatively impacted surface temperatures.

We evaluated the thermal surface inactivation of dried-down spot-inoculated *E. faecium* on stainless steel coupons (10.2 x 10.2 $cm^2$) during brief (2, 5, 10 s) stationary superheated steam exposures of 397°C (2.5 cm nozzle-surface distance and 23.5°C ambient temperature). Coupons were inoculated at three locations: geometric center, and at 2.3 and 4.6 cm from the geometric center. Superheated steam achieved the microbial reduction of 4.78 ± 0.87 log CFU/$cm^2$, 7.72 ± 1.50 log CFU/$cm^2$, and 9.60 ± 0.13 log CFU/$cm^2$ at the impingement point for 2, 5, and 10 s, respectively. At 2.3 and 4.6 cm from the geometric center, reduction was highest during 10 s at 5.11 ± 1.87 log CFU/$cm^2$ and 2.81 ± 0.67 log CFU/$cm^2$, respectively (**Fig. 1**). Results indicated that distance on the surface from the impingement point and time significantly increase microbial inactivation ($p < 0.05$).

We assessed the effects of training and experiential learning on manual operation of superheated steam for thermal surface inactivation of dried-down spot-inoculated *E. faecium* on stainless steel coupons (30.5 x 30.5 $cm^2$). Human subjects (n=24) completed a two-day training about personnel safety or operation of the equipment, plus personnel safety. The untrained group had the largest average distances of 17.2 ± 13.2 and 15.0 ± 10.8 cm and shortest treatment times of 55 ± 34 and 63 ± 31 sec over day 1 and 2, respectively. The gained knowledge group decreased distance to 5.6 ± 6.2 cm and increased treatment time to 190 ± 180 sec over the two days. The training interventions and self-reported distance significantly impacted the distance and treatment time ($p < 0.05$), but experiential learning only influenced the treatment time. Microbial inactivation of *E. faecium* significantly increased with training interventions and experiential learning ($p < 0.05$), not experience with food safety or industry (**Fig. 2**). The highest average reductions on day 1 and 2 were by the retained knowledge group at 2.60 ± 1.57 log CFU/cm$^2$ and 3.56 ± 1.27 log CFU/cm$^2$, respectively, while the untrained group achieved the smallest reductions at 0.25 ± 0.28 log CFU/cm$^2$ and 0.36 ± 1.27 log CFU/cm$^2$. These findings suggest that equipment modification would improve microbial inactivation outcomes using superheated steam by improving ease of use.

*Objective 2: Quantify the change to ambient relative humidity (RH) as a consequence of the extended use of SHS in indoor spaces as a function of steam flow rate, duration of treatment, size of enclosure, room ventilation, and air handling system.*

*Methods:*

Facilities: In total, 12 indoor or semi-enclosed spaces were tested in this study. The room length, width, and ceiling height were measured to estimate volume in cubic meters. Qualitative information on the ventilation (central air, unit ventilation, or natural) and features disruptive to air flow (e.g., fans, density of equipment) was collected. The spaces were categorized into four types based on size and ventilation rate: A) large facilities with high ventilation rates; B) large facilities with low ventilation rates; C) small facilities with high ventilation rates; and D) small facilities with low ventilation rates, where an air exchange rate per hour (ACH) >60 was defined as a high ventilation rate and <60 ACH was defined as a low ventilation rate. Large facilities were categorized as >110 m$^2$, and <110 m$^2$ was defined as a small facility.

Treatment: The superheated steam unit was positioned in the center of the spaces which varied in size, air handling system, and ventilation rate. Data loggers located near (0.3 and 1.5 m [1 and 5 ft]) environmental variables (superheated steam nozzle, entrances, and vents) monitored the change in RH and temperature within these facilities.

*Results:*

The goal of this study was to characterize the change in RH and temperature within twelve enclosed and semi-enclosed indoor spaces during prolonged (up to 5 h) superheated steam use at 135°C. Superheated steam application did not significantly ($p > 0.05$) increase the ambient temperature nor RH among all spaces. The maximum increase in RH and temperature change were 47% (0.3 m distance from steam source, small facilities with high ventilation rate) and 9.3°C (0.3 m distance from steam source, large facilities with low ventilation rate), respectively, when examining all facility spaces over a 5 h treatment. However, at the location immediately (0.3 m) in front of the superheated steam nozzle, a significant increase in RH ($p < 0.001$) and temperature ($p < 0.001$) was observed (**Fig. 3**); similarly, steam cooling and limited surface condensation occurred. The results suggest that prolonged superheated steam exposure did not substantially increase the RH or temperature of the processing environment.

*Objective 3: Develop key performance indicators around SHS efficacy, implementation costs, and safety standards for produce industry adoption of this novel technology.*

*Willingness-to-Pay:* An experiment with semi-randomly selected respondents was conducted between January and May 2023 across the United States. A discrete choice experiment (DCE), previously known as conjoint analysis, was designed, implemented, and analyzed to understand how different factors associated with the consideration of a new sanitation technology can affect the food industry preferences for further development and purchasing opportunities. The study was reviewed and approved by the Cornell University Institutional Review Board (IRB) under

Protocol Number IRB0145021. The survey was generated through Qualtrics™ software, Version 01/2023 (© 2023, Qualtrics, Provo, UT, USA). Participants were recruited via email and in person, through different strategies, such as international associations, industry directory lists, professional contacts from the research team, extension offices, and outreach agencies. More than 2,000 emails with an embedded Qualtrics link and QR code, were sent to industry professionals to invite them to participate in the survey. The choice experiment presented participants with a simulated purchase decision situation using two alternative technologies which contained the same attributes, but in different levels or values. The resulting model included three blocks, with ten choice sets per respondent. All attributes at different levels were randomly assigned. Each containing choice set provided two possible responses, "I would purchase technology 1" or "I would purchase technology 2", and a third "opt-out" option, "I would not purchase either".

A total of 63 responses from the produce industry were collected, with 1,794 observations. Respondents were willing to pay significantly more for a sanitation technology that reduced environmental *Listeria* positives (ELP) rate below the highest surveyed level of 10%. Respondents were willing to pay up to $446,500 for a 0.01% ELP rate, the lowest level surveyed. Similarly, respondents were willing to pay significantly more for sanitation technologies with a reportedly high level of efficacy reported as percent microbial reduction. Respondents were willing to pay up to $237,900 more for sanitation technologies able to achieve a reduction of at least 99.99% in the microbial target compared with sanitation technologies only able to achieve a reduction of 90%, the least effective level surveyed. The level of maintenance the new technology required was also a statistically significant factor in purchasing decisions. By contrast, labor, water and chemical use, and the wear-and-tear on equipment did not significantly affect purchasing decisions.

*Employee safety:* Superheated steam is a surface sanitizer with temperatures ranging from 125°C to >300°C. Evaluating the occupational hazards to operators using this technology is important as superheated steam is invisible to the naked eye. This study assessed potential occupational hazards, regulatory requirements, and operators' perceptions of personal safety for superheated steam use. The 29 CFR 1910 General Industry Code and General Duty Clause were identified as relevant requirements of the Occupational Safety and Health Administration regulations. Consequently, operators should don personal protective equipment including goggles, heat and waterproof gloves, and slip and impact-resistant, waterproof shoes. Employee safety training is needed to prevent accidents. To evaluate operators' perceptions of safety hazards, subjects (n=24) were presented with safety training and were then asked to operate a pilot-scale unit and provided feedback via survey. Before the trial, seven respondents found the technology "very dangerous" or "dangerous," with no respondents perceiving it as "safe." After the subjects used the pilot-scale unit, the number of subjects who viewed the tool as "not very dangerous" (n=8) and "safe" (n=2) increased, though this was not statistically significant (**Fig. 4**). These findings elucidate the potential challenges associated with manual operation of superheated steam technology, offering insights for further improvements before use.

*Evaluation on different surface materials:* Microbial inactivation using superheated steam was studied on eight different food processing surfaces. This included stainless steel, concrete, plywood, leather, polytetrafluoroethylene (PTFE), silicon rubber, cotton, and cardboard. *Enterococcus faecium* was inoculated directly and equilibrated at 0.2 $a_w$. Coupons made from various test surfaces were treated by superheated steam at 150°C for 3 min. Treatment resulted in 10 $\log_{10}$ CFU reduction for most surface coupons except for cardboard (9 $\log_{10}$ CFU). Low hydrophobicity and high thermal inertia of surfaces appear to be correlated with microbial inactivation.

Prolonged exposure of superheated steam on various surfaces may damage the surfaces. For example, treatment may induce thermal stress cracks and corrosion. To evaluate this, selected surfaces (stainless steel, plywood, and silicon rubber) were treated with superheated steam at 150°C for 5 min once per week for 4 weeks. After the treatment each week, we monitored the change in roughness and hydrophobicity (contact angle) of the treated surfaces. A slight increase in the hydrophobicity of silicone rubber and stainless steel, but no significant change in roughness, was noted. In conclusion, within the tested conditions of the study, superheated steam did not adversely modify the properties of tested surfaces.

**Outcomes and Accomplishments**

The project provides critical efficacy data on commercial superheated steam units. We also assessed the use of commercial units on ambient RH in indoor facilities, surface material deformation, and worker safety. These findings clarified the benefits and drawbacks of manually operated superheated steam units. We hope the results from this project can be used to improve the design of these tools in the future as well as help the industry make purchasing decisions about when to invest in this new technology. In addition to sharing our results through the scientific conferences and publications described below, a press release about our research was picked up by Food Safety News and SQFI.

**Summary of Findings and Recommendations**

- At the target operating temperature, superheated steam is effective at pathogen inactivation. Bench-scale and well-controlled experiments repeatedly demonstrate this.

- However, the temperature of the steam of manually operated units drops quickly as distance between the target surface and the nozzle increase. That means that sanitation staff cannot treat large surface areas quickly with the manually operated units. To be effective, the wand has to be held close to the surface and that introduces practical limitations. This is the greatest drawback of the current commercial units identified in our research. This also suggests that sites using these tools should include methods to monitor and verify the application of superheated steam to ensure they are achieving the intended microbial lethality.

- The volume of water introduced via the superheated steam is not enough to increase ambient RH in indoor spaces, even after extended (5 h) use. However, some condensation can be formed on surfaces if they are ~1 ft in front of the unit where the steam has begun to cool.

- At targeted treatment temperatures, surface material type generally did not impact microbial inactivation. While some materials may be sensitive to superheated steam deformation, additional work is needed to see if treatment of equipment joints (e.g., where to components meet, particularly if they are made of different materials).

- There are no dedicated OSHA standards for manually delivered superheated steam, but worker safety training and Personal Protective Equipment can be implemented to comply with the General Duty clause.

## APPENDICES

### Publications and Presentations

*Publications:*

Shiyu Cai, Hyeon Woo Park, Jingzheng Feng, Jakob Baker, V.M. Balasubramaniam, and Abigail B. Snyder. 2024. Ambient temperature and relative humidity remained stable after prolonged application of superheated steam in enclosed spaces. Food Protection Trends. *Accepted, Pending Publication.*

Three additional manuscripts are under review.

*Presentations:*

CPS Research Symposium, 2023. Practical application of superheated steam to harvesting, processing, and produce packing tools and equipment. [Short Talk + Poster].

CPS Research Symposium, 2022. Practical application of superheated steam to harvesting, processing, and produce packing tools and equipment. [Poster].

V.M. Balasubramaniam and Abigail B. Snyder. Technical Symposium. Cleaning Without Water. *Institute of Food Technologists (IFT) Annual Meeting, Chicago, IL*. July 2022. On-Demand.

A.B. Snyder. 2022. Tackling sanitation in low moisture food systems. Department seminar offered at: Michigan State University, Virginia Tech University, University of Georgia, and Penn State University.

Maria Amalia Beary, Jakob Baker, V.M. Balasubramaniam, and Abigail B. Snyder. 2024. Evaluation of occupational safety risks and perceptions by human subjects in the manual application of superheated steam as a new surface sanitation technology in processing industries. Submitted IAFP Abstract.

Jakob Baker, Yadwinder Singh Rana, Long Chen, Maria Amalia Beary, V.M. Balasubramaniam, and Abigail B. Snyder. 2024. “Dry Steam” treatments result in rapid microbial inactivation in a narrow radius surrounding the nozzle, making effective manual operations of commercial-scale units difficult for human users. Submitted IAFP Abstract.

Maria Amalia Beary, Jie Lie, Miguel Gomez, and Abigail B. Snyder. 2024. Willingness to pay for new sanitation technologies in food industries: A comprehensive choice analysis for purchasing preferences among manufacturers. Submitted IAFP Abstract.

### Budget Summary

A total of $396,178 in research funds was awarded for this project, and the majority of funds were spent.

**Figures 1–4** (see below)

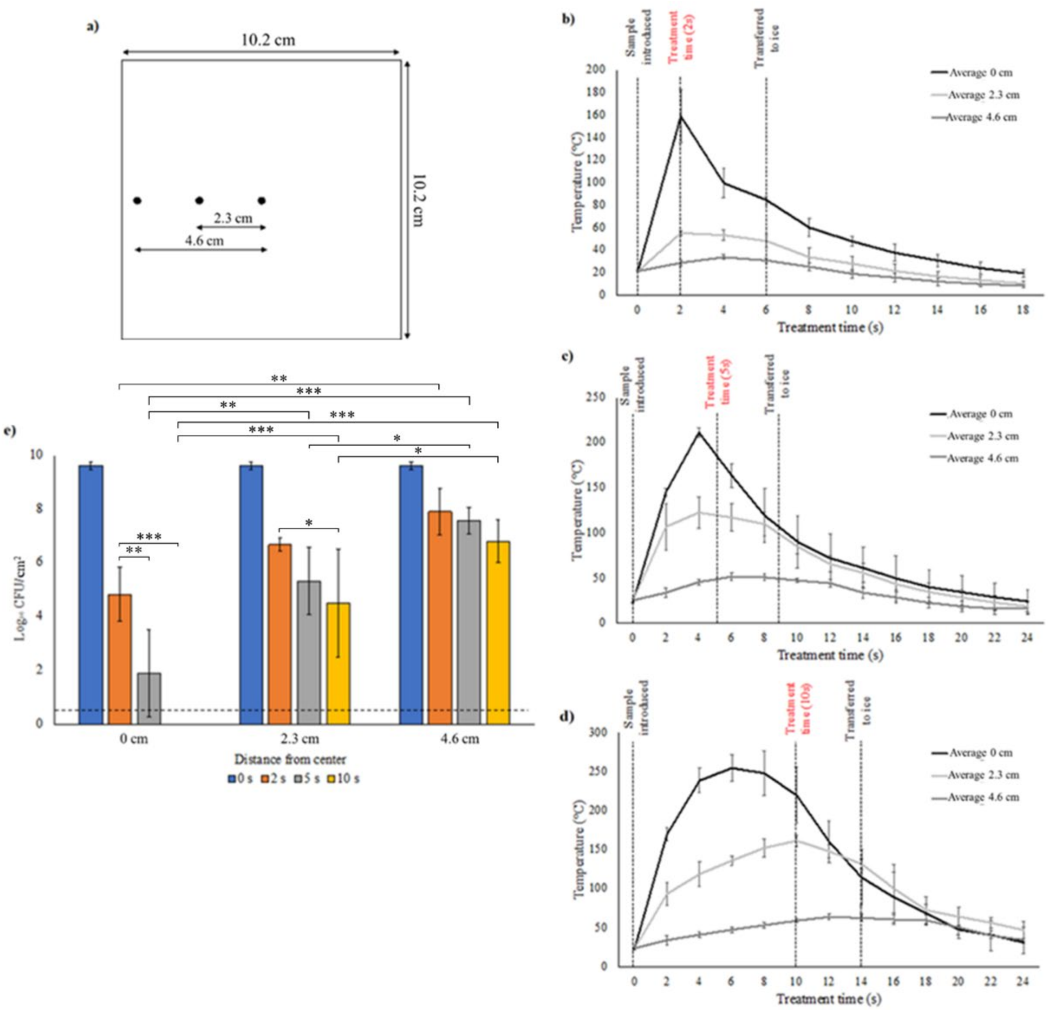


**Figure 1:** (a) Sampling locations on stainless steel coupons (*length x width x thickness:* 10.2 cm x 10.2 cm x 0.05 cm). Surface temperature profile at sampling locations on stainless steel coupons following (b) 2 s, (c) 5 s, and (d) 10 s superheated steam exposure at 2.5 cm distance from superheated steam nozzle. Termination of treatment exposure designated with red text. (e) Survival of *E. faecium* NRRL B-2354 at varying sampling locations on stainless steel coupons after 0, 2, 5, and 10 s superheated steam exposure. *Dashed line represents limit of detection: 0.52 $log_{10}$ $CFU/cm^2$ for dried-down spot inoculation method.* ***$p<0.001$, **$p<0.01$, *$p<0.05$.

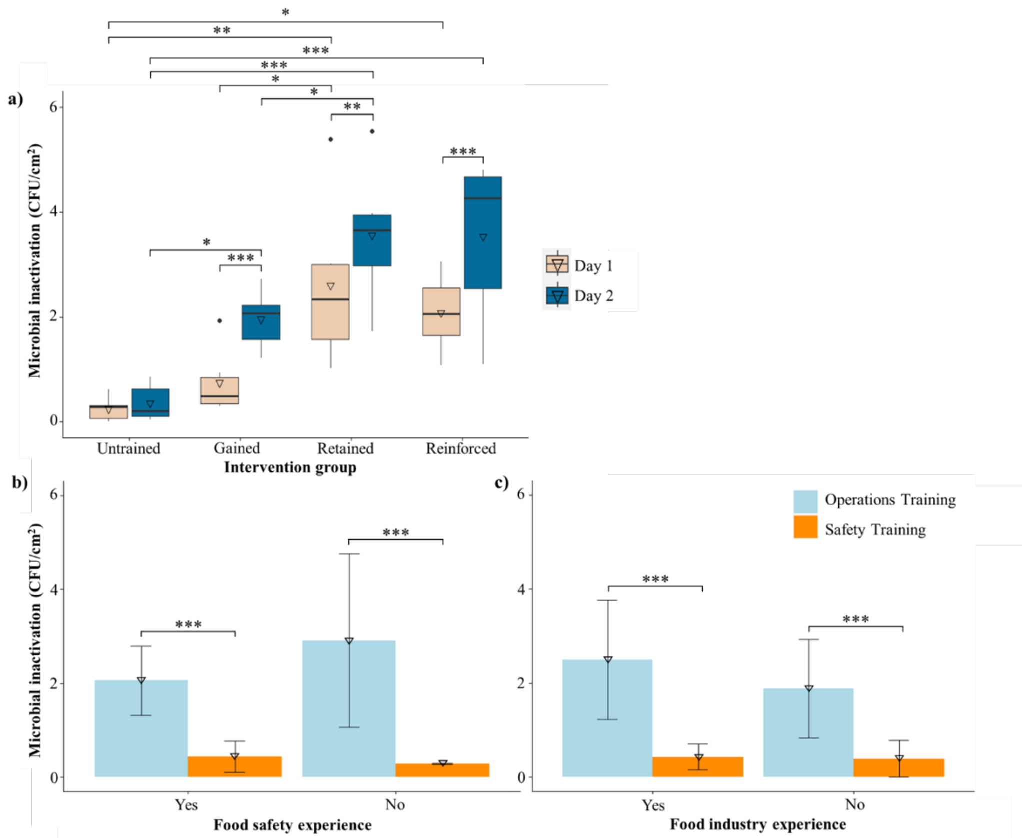


**Figure 2**: Microbial reduction of *E. faecium* NRRL B-2354 on stainless steel coupons (*length x width x thickness:* 30.5 cm x 30.5 cm x 0.28 cm) during manual operation of commercial-scale superheated steam unit by human subjects within (a) different intervention groups over 2 days, and based on prior experience with (b) food safety and (c) food industry. ***$p<0.001$, **$p<0.01$, *$p<0.05$.

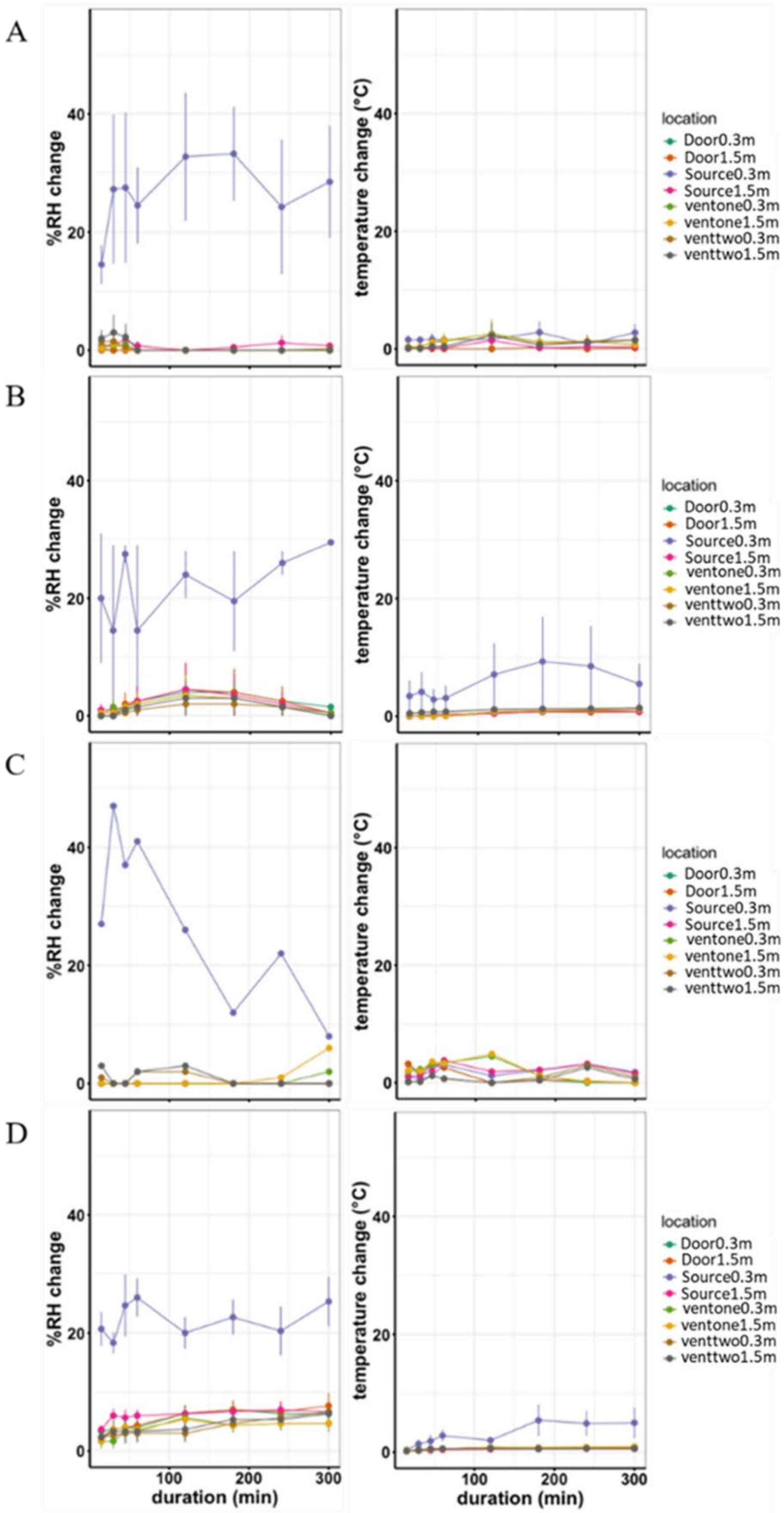


**Figure 3:** Average RH (left) and temperature (right) during superheated steam use for 5 hours in: (A) large facilities with high ventilation rate (n = 4); (B) large facilities with low ventilation rate (n = 2); (C) small facilities with high ventilation rate (n = 1); and (D) small facilities with low ventilation rate (n = 3).

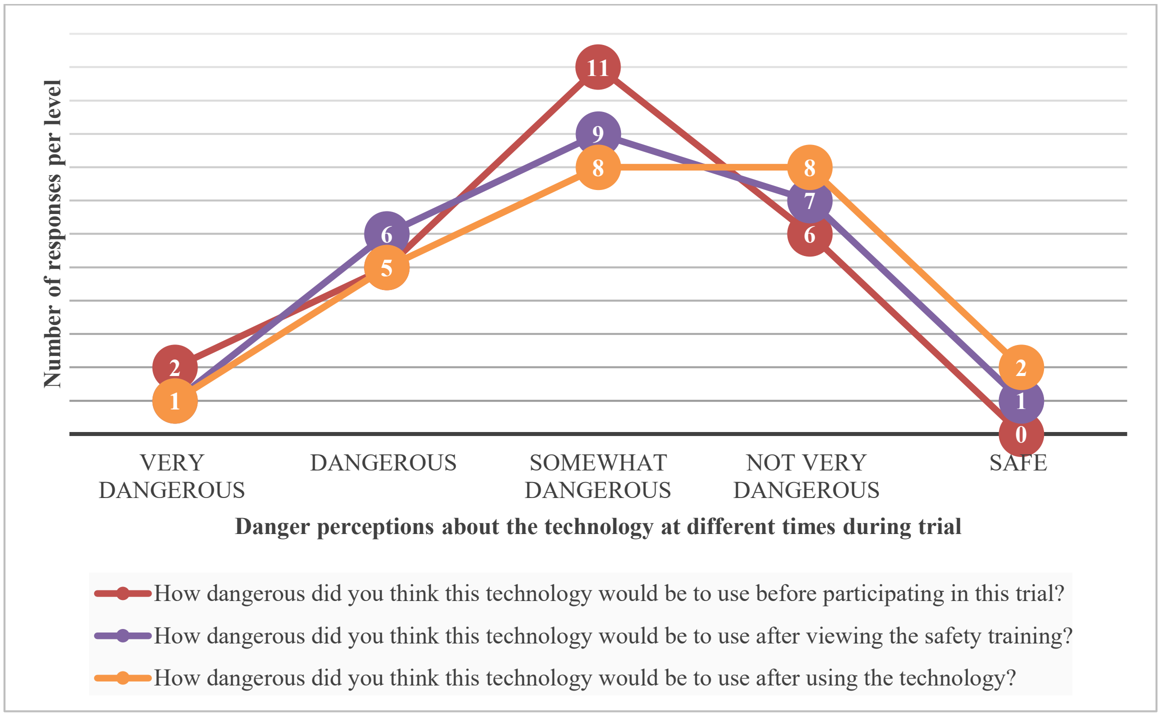


**Figure 4:** Perceived level of danger of the technology evaluated at three different time points. Numbers represent the respondents in each category.

**References cited:**

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