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Delphi expert elicitation to prioritize food safety management practices in greenhouse production of tomatoes in the United States

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Abstract

Most of fresh tomatoes sold in the United States (US) are grown using protected agriculture. The risk of contamination and severe disease outbreaks in humans due to foodborne pathogens linked to fresh produce are a constant threat to the public and the industry. To date, there are limited tools to prioritize food safety management practices in commercial greenhouses to reinforce food safety in a timely manner. One rapid cost effective approach, originally applied in education and healthcare, is the Delphi method that uses expert opinion to quantify and rank priorities.

An iterative systematic Delphi expert elicitation approach was used to prioritize management factors for the reduction of foodborne pathogen contamination in tomato greenhouses in the US. A validated online survey addressing eight thematic areas (water management, workers, environment and greenhouse design, equipment sanitation, waste management, animal intrusion, traceability, and propagation) was discussed among 20 individuals internationally recognized as experts in fresh produce production in protected agriculture, foodborne pathogens, and food safety theory and practice. Consensus rankings of activities and practices most likely contributing to microbial contamination and its mitigation were determined.

Food safety priorities to prevent contamination of greenhouse tomatoes, in order of significance (*i.e.*, ranking scale, weighted average; 1 lowest, 5 highest), included handwashing (4.67), environmental controls (4.32), enforceable worker health policy (3.94), cleaning and sanitation of reusable plastic containers (3.94), reused retail-ready containers (3.89), and irrigation water testing for human pathogens (3.84) to prevent contamination of greenhouse tomato.

The majority of experts indicated that contaminated greenhouse surfaces that are in contact (direct or indirect) with the fruits are important sources of pathogen transfer to fresh tomatoes, highlighting the need for environmental controls in greenhouses. Importance of adequate worker management practices including handwashing and health policy highlights the role of worker education in reducing the risks of foodborne outbreaks linked to greenhouse grown produce. This report illustrates the benefits of using Delphi approach to improve food safety in greenhouses. The provided priority list can be used by growers to guide the routine food safety practice implementation procedures.

Keywords: Greenhouse, vegetable, tomato, Delphi, food safety, contamination risk, foodborne pathogens

1. Introduction

The United States (US) Food and Drug Administration (FDA) Food Safety Modernization Act (FSMA) actively provides regulations on food safety of fresh produce (Long, Strawn, Eifert, & Rideout, 2016). The greenhouse vegetable production is covered under Standards for Growing, Harvesting, Packing, and Holding of Produce for Human Consumption (US Food and Drug Administration, 2015) which regulates primary production of fresh fruits and vegetables on the farm. Practices to prevent entrance and dissemination of human pathogens in the greenhouse tomato production environment (environmental controls) within the greenhouse enclosures are required by the Rule (US Food and Drug Administration, 2015), and will have to be implemented by greenhouse growers. By consulting experts on the topic, we aimed at determining which of the management practices and environmental factors were most relevant to control human pathogens in tomato greenhouses.

Protected agriculture, notably the greenhouse produce industry, has been rapidly expanding over the last decade due to increased consumption and demand for year-round fresh produce. Approximately 55% of all fresh tomatoes sold in the US market today are greenhouse grown (Brauther, 2010). Contamination with human pathogens, potential foodborne disease outbreaks, and recalls due to microbial contamination are a threat to the public and industry sustainability.

While environmental conditions in the greenhouse, such as temperature and humidity, are maintained to enable intensive production, they are highly conducive for survival, dissemination and growth of foodborne pathogens, such as, *Listeria monocytogenes*, Shiga toxin-producing *Escherichia coli* (STEC) and *Salmonella* spp. The potential for contamination of greenhouse grown produce is well documented (Luedtke, Chapman, & Powell, 2003; Manios et al., 2006; Orozco, Rico-Romero, & Escartin, 2008). In addition to the 2013 outbreak of *Salmonella* Saintpaul in the US from greenhouse cucumbers (Hanning, Nutt, & Rieke, 2009), *Salmonella* spp. was previously isolated from tomatoes grown in greenhouses and from puddles and greenhouse soil (L. Orozco et al., 2008; R. Orozco et al., 2008). Management practices influence entry and transmission of human pathogens in the greenhouse. *In vitro* survival studies found that once *Salmonella* spp. was established on the surface of leaves or fruits, it could persist for extended periods of time under typical conditions that are maintained in greenhouses (temperature 75-85F, relative humidity 80-90%) and humidity and be transferred to non-contaminated surfaces or fruit in any downstream events (Rathinasabapathi, 2004; Shi et al., 2009). Because the number of possible combinations and interactions at one stage of greenhouse production can have significant impacts throughout production, the food safety outcomes may be uncertain and difficult to predict and measure (Yoshida, 2016).

Resolution of many of the uncertainties related to management practices may be best achieved by adopting a prioritization approach. However, management practices are difficult to prioritize. The prioritization process should be based on knowledge of severity and probability of a microbial hazard, and must be science-driven involving interdisciplinary teams (Hoffman & Hammonds, 1994). In addition, a thorough understanding of management strategies as well as the paths of introduction and transmission of human pathogens is required. Several methods have been used in human health clinical practices, and more recently in farming (Soon, Davies, Chadd, & Baines, 2012), including Delphi methods to prioritize practices and design consensus guidelines. First adopted by the US RAND Corporation for its research purposes in the 1950s, the Delphi method is based on an iterative set of questionnaires designed to elicit experts' knowledge and achieve consensus (Heiko, 2012). The Delphi process is comprised several rounds of surveys in which experts are selected for their in-depth theoretical and practical knowledge of the discipline. Despite the long-standing record of benefits derived from Delphi elicitation, such an approach has not been widely used in the food industry to promote food safety.

The objective of this study was to formulate a consensus on prioritization of the broad range of greenhouse management practices in commercial hydroponic tomato production and propose a list of food safety priorities for industry application, using the Delphi method to elicit and synthesize the opinions of experts on food safety of fresh produce research and practice in greenhouse tomato.

2. Material and Methods

2.1 Recruitment of expert panel and strategy

Professionals with expertise in food safety of fresh produce were approached to participate in the study. We used listserves of three fresh produce professional groups: International Association of Food Protection Fresh Produce Professional Development Group, Center for Produce Safety, and a United States Department of Agriculture multistate project membership (S1056) to reach the experts nationally and internationally, and invite them to participate in a web-based Delphi elicitation process. Total membership for all three groups was approximated to 3,000. The selection criteria required that participants have expertise in microbial food safety of fresh produce and knowledge of fresh produce production, with an emphasis on greenhouse production systems. Experts were contacted via email containing a brief explanation of study objectives, the Delphi procedure, and the request for consent. The first 20 internationally and nationally recognized experts consenting to participate in the study were included. Participation was voluntary and no incentives were provided. All study procedures were approved by The Ohio State University Institutional Review Board (IRB) for Social and Behavioral Research with Humans (protocol 2012E0470). The participants were required to indicate the highest granted degree and years of experience in the field of food safety. Experts provided their opinion anonymously and independently through questionnaires (von der Gracht 2012). The experts were not required to be physically present, allowing for an unconstrained geographic scope (Kendall et al., 2003). After the responses were collected, participants received controlled, group feedback and were able to alter responses or justify their answers, engaging in interactive discussion that was not biased by the group dynamics or opinion leader influences (Soon et al., 2012). Questions were reiterated until stability of responses or consensus was achieved (von der Gracht 2012).

2.2. Development and administration of surveys

An extensive on-site survey of management practices was previously conducted in 26 greenhouses in the US, Canada, Mexico, and Guatemala (Ilic et al., 2015). Management practices (n=293) in geographically diverse greenhouse operations, highly heterogeneous in size and type, were catalogued in a preliminary study. Propagator and producer process flow diagrams were constructed for large and small greenhouses (Ilic, 2012) and the management practices were classified through an operational risk assessment (Gkogka et al., 2013). Out of all identified practices, those with uncertain food safety outcomes (n=68) were selected by the multidisciplinary research team and classified into the following modules: a) water management, b) worker management, c) greenhouse environment and design, d) sanitation, e) animals, f) waste, g) traceability, and h) propagation. The survey questions for round one and two are available in the Supplement Tables ST1 and ST2. To elicit expert opinion about the food safety risks related to these management practices, the first round questionnaire was constructed. The questionnaire consisted of 27 questions that were formulated to assess the importance of each identified management practice to contaminating or preventing the contamination of plants, tomato fruit or the greenhouse environment. The survey was developed and pre-tested by three independent reviewers. It was administered using web-based survey software program (SurveyMonkey Inc., Palo Alto, CA). Round one survey response were designed as an ordinal five point Likert-type scale, ranking the importance of factors from 5=highly important to 1=not important, or agreement with the statements from 5=strongly agree to 1=do not agree. The participants were additionally asked to solve a water management scenario and provide comments to justify their responses. The survey was open for 21 days and all data were collected within this time frame. The data were collated, coded and tabulated. The results were expressed as frequencies and graphical summaries (Sullivan & Artino Jr, 2013). Consensus (or a stable response) was achieved on a question to question basis if at least 70% of the respondents were in agreement and the composite score fell in the “important” or “not important” range, or a 10% or lower change in response distributions was achieved (Heiko, 2012). The results of the first round were presented to the experts as feedback prior to their participation in the second round.

The Delphi process was re-iterated in the second round for items without consensus (agreement < 70%). Questions for round two were formulated taking into consideration the expert input collected in the first

round. The round two questionnaire included 15 questions classified into the same modules as those in round 1, using a four point Likert-type ordinal scale where the neutral response was omitted (Supplement Table ST2) (5=highly important, 1= not important) or agreement with the statements (5=strongly agree and 1=do not agree) (Heiko, 2012). The experts were further asked to provide a brief justification for their response pertaining to the water management scenario. The second round survey was also open for 21 days and the data were organized as described for the round one survey. The consensus and the stability of the group answers were used as the process stoppers (Akins, Tolson, & Cole, 2005; Gordon & Pease, 2006; Gurrera et al., 2011). The stability was defined as the percent change in distributions from the previous round. A consistent decrease of the coefficients of variation between the first and the second round, indicated an increase in consensus (greater movement toward the mean). Consensus or stable responses were achieved for all questions after the second round. As the third round of the survey would not add to the understanding of risks related to management practices provided by the previous two rounds, the process was concluded (Hopf, Francis, Helms, Haughney, & Bond, 2016).

2.3. Statistics and data analysis

Data were managed in Excel (Microsoft 2010; Redmond, WA). Descriptive and statistical tests were performed in SPSS (IBM Corp. 2015; Armonk, NY). The results were summarized using frequencies and graphs. Summarized first round outcomes (medians, upper/lower quartile and percent agreement) were sent to participants prior to the second round. Expertise levels were ranked using weighted averages for each pathogen and each aspect of food safety. The weighted averages, upper and lower quartiles, percent agreement and importance levels were presented in tables. The items ranked in both rounds are shown in the same table and organized per module. Likert scale responses were analyzed by weighted averages using frequencies as weights and used for priority scoring (Peter, Visser, & de Jong, 2008). Weighted averages were calculated as the sum of the products for each response divided by all of the participants who committed an answer (on a scale of 1-5), divided by the total number of respondents (Peter et al., 2008). The importance was ranked as low (priority score 1.00-2.49), medium (2.50-3.49) and high (priority score 3.50-5.00). Heatmap analysis for visual representation of expertise, expert responses to each question (Cugnata, Kenett, & Salini, 2016), and clustering bias analysis with Kolmogorov-Smirnov (KS) test using were performed in R Studio (Boston, MA).

3. Results

The full greenhouse production process, from the seed to the final product is summarized in Figure 1. Prioritization of the majority of management practices is challenging due to the lack of data (Butler, Monroe, & McCaffrey, 2015) specific to greenhouse settings. A formal elicitation of expert opinion was used to rank the food safety practices and determine the priorities for industry.

3.1 Participation and self-reported expertise

The experts (n=20) were nationally and internationally recognized individuals from the US, Canada, Central and South America, and Europe. The majority of participants held doctorate degrees (PhD) (85.0%; n=17) in a field related to food safety; two participants held master's and one held a bachelor's degree. The expert group included heterogeneous stakeholder interest, as the participants were involved in academic (n=8) or government research (n=5), extension (3), government regulatory services (n=2) and private industry (n=2). Thirty percent of experts (n=6) had over 20 years of experience related to food safety, ten had 6-20 years (50.0%), and four (20.0%) were working in a food safety related field in the last 1-5 years. Overall, the group self-reported the highest level of expertise for *E. coli* (STEC and generic) (3.32), *Salmonella* spp. (n=20; 3.11) and *L. monocytogenes* (n=20; 3.0, Table 1). High expertise areas are visualized in Figure 2a, with more experienced participants clustering higher in self-reported expertise, as expected (Figure 2c, KS, $P=0.022$). The response bias due to participants' years of experience was absent (Figure 2c KS, $P=0.1616$). The consulted experts answered a total of 42 questions in two Delphi rounds (27 questions in round 1; 15 in round 2) to achieve consensus for each item (agreement $\geq 70\%$). The responses scaled 1 (lowest; not important; disagree) to 5 (highest; very important, strongly agree) were used as a ranking system based on their priority scores.

3.2. Water and water management

Most experts (79.8%) thought that irrigation water was an important source of contamination of greenhouse vegetables with human pathogens. Accordingly, testing of irrigation water for human pathogens was considered to be a valuable tool in controlling contamination with human pathogens in the greenhouse (Table 2). While there was an agreement among experts that testing of irrigation water for human pathogen indicators (e.g. coliforms/generic *E. coli*) was important in controlling the contamination in the greenhouse, the testing of irrigation water for human pathogens (*Salmonella* spp., *E. coli* O157, and *L. monocytogenes*) was ranked as a higher priority.

Experts gave their opinion of the appropriate time interval required before any of tomatoes could be harvested in a commercial hydroponic greenhouse setting and that could be safely sold for fresh consumption after a pathogen was detected in irrigation water. In a set scenario where “a human pathogen was detected in water, sampling of harvest-ready tomatoes was performed using a statistically appropriate sampling design, the pathogen was not detected on fruits, the irrigation water was treated with the UV light before use and no sequential water tests detected any pathogens” (Table S1), the experts identified a number of factors to be considered when making such a decision. These included 1) type and concentration of pathogen detected in water 2) whether there is a zero tolerance policy for the pathogen and 3) water application modality (foliar vs. soil). Priority scores are listed in Table 2.

3.3. Worker management

All experts (100%) agreed that hand hygiene was important in reducing risk of contamination of greenhouse vegetables with human pathogens (4.67). Handwashing was ranked the most effective strategy (Table 2) in reducing contamination with human pathogens in greenhouses, followed by enforceable health policy and proper gloving, footbaths, and designated footwear and clothing (Table 2). The majority of experts (93.0%) thought that people occasionally may introduce human pathogens in the greenhouse. Restricted access to visitors and non-designated workers, however, was not considered to be an effective strategy to reduce contamination.

3.4. Environmental controls, surfaces and management practices

Experts agreed (84.0%) that the presence of human pathogens in the greenhouse production environment was highly important to contamination with human pathogens (4.32). Surfaces that were considered important for contamination of greenhouse produce are listed in Table 2. Type of greenhouse construction material used (i.e. polycarbonate, glass or nylon), was deemed of low importance to food safety. The type of plant growing medium (i.e. coconut coir, soil mineral wool, vermiculite or perlite) was ranked higher in terms of importance than that of construction material.

Planting different species of greenhouse vegetables, increasing planting density, bay size, interplanting (planting new crop in between old plants close to the end of their annual cycle to achieve perpetual harvest) and monitoring for plant pathogens were considered of low importance for contamination with human pathogens, while the practice of leaving plant trimmings under the troughs was reported to be of medium importance for human pathogen transmission to fruit (Table 2). The distance of waste disposal from the growing crop was ranked as highly important to controlling contamination of greenhouse tomato (3.78). Half of the experts thought that the waste disposal sites should be no closer than 100 feet (30.5 m) from the greenhouse (50.0%) while 35.7% of the experts thought the distance should be no closer than 250 feet (76.2 m).

3.5. Contamination during propagation of tomato plants

Experts agreed (89.5%) that contamination of tomato plants during seedling propagation poses a food safety risk for greenhouse produced tomatoes. Practices that were most important to contamination of tomato transplants with human pathogens were employee hygiene and health and mode of seedling irrigation (i.e. flood, ebb and flow, or overhead) (Table 2). Simultaneous propagation of multiple produce species and propagation of ornamentals in the same propagation area were ranked low priority for seedling contamination. The panel did not agree about the importance of seed contamination (52.6%

round 1; 50.0% round 2, %change <5) or pesticide application (50.0% round 1; 50.0% round 2, %change 5%).

3.6. Contamination from animals

The presence of animals inside the greenhouse presented was identified as a high risk for contamination of fruit with human pathogens. The presence of rodents and birds was ranked the highest (4.26), followed by birds (4.21) and domestic cats (4.21). Among insects, pollinators were ranked the lowest priority (1.84), while the highest ranking was assigned to the presence of flies (3.53; Table 2). According to the experts, the distance of livestock and poultry operations was an important factor in contamination of greenhouse produce with human pathogens (73.77%; 4.26). Topography of terrain, prevailing winds, and greenhouse construction design were factors listed by the experts that would affect their decision on the appropriate distance required to assess risk.

3.7. Traceability

Ability to trace the produce back to the plant of origin was considered an important factor in reducing the risks of human pathogens in greenhouse produced tomato. The ability to trace the greenhouse produce to the person who harvested the fruit was considered to be of medium importance (Table 2).

4. Discussion

This report illustrates the benefits of using the Delphi approach to improve food safety in greenhouse vegetable production. The FDA Food Safety Modernization Act bills are shortly expected to be actively implemented in the fresh produce industry for covered produce and covered operations (US Food and Drug Administration, 2015). In this study we prioritized greenhouse management practices that could improve food safety and prevent contamination, and produced a list of priorities ranked based on priority scores (weighted average of item relevance for industry application, both using the Delphi method).

Delphi has been widely accepted as a research technique since its value has been scientifically and practically proven. Delphi panels have been used as a “gold standard” (Rolfes, Kolfchoten, Hunsel, & Puijenbroek, 2016) in studies to quantify reliability of other operating assessment tools in human medicine and public health. For instance, it has been used by international societies to develop clinical practice guidelines for gastrointestinal endoscopy (Rees et al., 2016), and to improve the applicability of guidelines for skin cancer (Lubeek et al., 2016). In a public health pharmacovigilance study, Delphi showed that established operating assessment tools had insufficient validity (Rolfes et al., 2016). In the present study we consulted 20 experts, which is an appropriate number based on previous studies and recommendations (Chu & Hwang, 2008; Gordon & Pease, 2006; Grundy & Ghazi, 2009).

By using the ranking based- scoring system, the present Delphi elicitation identified based on consensus agreement of >70% as the top management priorities : *i*) enforce handwashing throughout production, *ii*) monitor and ensure the quality of the irrigation water is optimal and follow basic standards for safe produce production, *iii*) clearly define effective worker health policies in which temporal or spatial restrictions could be implemented to prevent ill workers from contaminating the food product or the greenhouse environment and, *iv*) provide clearly written and implemented standard operating procedures to ensure that human pathogens are absent from the greenhouse environment (environmental controls) including sanitation of surfaces, equipment, and floors. In addition, a clear understanding of food safety practices for propagation greenhouses is critical to prevent the contamination with pathogens and ingress into the production greenhouses (**Tables 2 and 3**). Specific criteria for the assessment, improvement and the establishment of proper practices have been extensively discussed in the scientific literature [for instance, (Greene et al., 2008; Ilic, 2012; Jahns & Smeenk, 2009; Olaimat & Holley, 2012; Oliveira, Viñas, Usall, Anguera, & Abadias, 2012; Park et al., 2012) and guidelines specific to tomato (US Food and Drug Administration, 2008) exist to assist growers in determining whether any of the priorities herein listed merit special attention. Providing specifics on these rapidly evolving priority topics falls outside of the scope of this manuscript.

Similar to many other methods of knowledge synthesis, the use of Delphi has been shown to have some limitations on reproducibility and transparency. In an attempt to control for such limitations, we conducted two rounds of interviews. Despite this well-established method for correction, it is important to highlight that future prioritization endeavors, could consider the use and implementation of other methods of expert opinion gathering, and complementing them with scoping and systematic reviews, meta-analyses, and multi-criteria decision making approach. To further strengthen the elicitation process, described herein, the Delphi panel based prioritization may be complemented with other methods used in public health and education (Yoshida, 2016). It is likely that the combination of complementary elicitation methods, together with established principles of critical control point determination (including Hazard Analysis Critical Control Point based approaches) would be most effective in providing a more integrated holistic approach to food safety. Additionally, stakeholder participation would further increase the implementation of and the compliance with food safety guidelines through direct input from industry and consumers.

5. Conclusion

In this report we explored a wider list of food safety control measures in greenhouse tomato production based on commercial growers in Canada, USA, and Mexico (Ilic, 2012) and created a priority based list of food safety practices. We showed that the Delphi approach can be used to assist growers and greenhouse associations to prioritize food safety hazards in the greenhouse and improve current practices by targeting these hazards. More broadly, the Delphi approach can help to determine applicability of any given practice; for instance, the assessment of effectiveness health policies or the effect of pathogen control within the different stages of plant development (Rees et al., 2016). Consideration of the top identified priorities will help to direct resources and efforts toward expanding and creating new evidence based production guidelines to protect the public from foodborne pathogen contamination greenhouse produce.

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7. Conflict of interests

The authors declare no conflict of interest.

8. References

- Akins, R. B., Tolson, H., & Cole, B. R. (2005). Stability of response characteristics of a Delphi panel: application of bootstrap data expansion. *BMC medical research methodology*, 5(1), 1.
- Brauther, C. (2010). Greenhouse produce: Challenges & opportunities. *Produce Business*.
- Butler, W. H., Monroe, A., & McCaffrey, S. (2015). Collaborative implementation for ecological restoration on US public lands: Implications for legal context, accountability, and adaptive management. *Environmental management*, 55(3), 564-577.
- Chu, H.-C., & Hwang, G.-J. (2008). A Delphi-based approach to developing expert systems with the cooperation of multiple experts. *Expert Systems with Applications*, 34(4), 2826-2840.
- Cugnata, F., Kenett, R. S., & Salini, S. (2016). Bayesian networks in survey data: Robustness and sensitivity issues. *Journal of Quality Technology*, 48(3), 253.
- Gordon, T., & Pease, A. (2006). RT Delphi: An efficient, "round-less" almost real time Delphi method. *Technological Forecasting and Social Change*, 73(4), 321-333.
- Greene, S., Daly, E., Talbot, E., Demma, L., Holzbauer, S., Patel, N., . . . Lynch, M. (2008). Recurrent multistate outbreak of Salmonella Newport associated with tomatoes from contaminated fields, 2005. *Epidemiology and infection*, 136(02), 157-165.
- Grundy, M., & Ghazi, F. (2009). Research priorities in haemato-oncology nursing: Results of a literature review and a Delphi study. *European Journal of Oncology Nursing*, 13(4), 235-249.
- Gurrera, R. J., Caroff, S. N., Cohen, A., Carroll, B. T., DeRoos, F., Francis, A., . . . Mahmood, A. (2011). An international consensus study of neuroleptic malignant syndrome diagnostic criteria using the Delphi method. *The Journal of clinical psychiatry*, 72(9), 1222-1228.
- Hanning, I. B., Nutt, J., & Ricke, S. C. (2009). Salmonellosis outbreaks in the United States due to fresh produce: sources and potential intervention measures. *Foodborne Pathogens and Disease*, 6(6), 635-648.
- Heiko, A. (2012). Consensus measurement in Delphi studies: review and implications for future quality assurance. *Technological Forecasting and Social Change*, 79(8), 1525-1536.
- Hoffman, F. O., & Hammonds, J. S. (1994). Propagation of uncertainty in risk assessments: the need to distinguish between uncertainty due to lack of knowledge and uncertainty due to variability. *Risk analysis*, 14(5), 707-712.
- Hopf, Y., Francis, J., Helms, P., Haughney, J., & Bond, C. (2016). Core requirements for successful data linkage: an example of a triangulation method. *BMJ open*, 6(10), e011879.
- Ilic, S. (2012). *Control and Prevention of Microbial Hazards in Greenhouse Tomatoes: Integrated Food Safety and Plant Health Approach*. Paper presented at the 2012 Annual Meeting.
- Jahns, T. R., & Smeenk, J. (2009). *Controlling the greenhouse environment*: University of Alaska Fairbanks, Cooperative Extension Service.
- Long, T. M., Strawn, L. K., Eifert, J. D., & Rideout, S. (2016). *The Food Safety Modernization Act's Produce Safety Rule*. Retrieved from
- Lubeek, S., Borgonjen, R., Vugt, L., Olde Rikkert, M., Kerkhof, P., & Gerritsen, M. (2016). Improving the applicability of guidelines on nonmelanoma skin cancer in frail older adults: a multidisciplinary expert consensus and systematic review of current guidelines. *British Journal of Dermatology*, 175(5), 1003-1010.
- Luedtke, A. N., Chapman, B., & Powell, D. A. (2003). Implementation and analysis of an on-farm food safety program for the production of greenhouse vegetables. *Journal of Food Protection®*, 66(3), 485-489.
- Manios, T., Papagrigoriou, I., Daskalakis, G., Sabathianakis, I., Terzakis, S., Maniadakis, K., & Markakis, G. (2006). Evaluation of primary and secondary treated and disinfected wastewater irrigation of

- tomato and cucumber plants under greenhouse conditions, regarding growth and safety considerations. *Water environment research*, 78(8), 797-804.
- Olaimat, A. N., & Holley, R. A. (2012). Factors influencing the microbial safety of fresh produce: a review. *Food Microbiology*, 32(1), 1-19.
- Oliveira, M., Viñas, I., Usall, J., Anguera, M., & Abadias, M. (2012). Presence and survival of *Escherichia coli* O157: H7 on lettuce leaves and in soil treated with contaminated compost and irrigation water. *International Journal of Food Microbiology*, 156(2), 133-140.
- Orozco, L., Rico-Romero, L., & Escartin, E. F. (2008). Microbiological profile of greenhouses in a farm producing hydroponic tomatoes. *Journal of Food Protection*®, 71(1), 60-65.
- Orozco, R., Iturriaga, M. H., Tamplin, M. L., Fratamico, P. M., Call, J. E., Luchansky, J. B., & Escartin, E. F. (2008). Animal and environmental impact on the presence and distribution of *Salmonella* and *Escherichia coli* in hydroponic tomato greenhouses. *Journal of Food Protection*®, 71(4), 676-683.
- Park, S., Szonyi, B., Gautam, R., Nightingale, K., Anciso, J., & Ivanek, R. (2012). Risk factors for microbial contamination in fruits and vegetables at the preharvest level: a systematic review. *Journal of Food Protection*®, 75(11), 2055-2081.
- Peter, M., Visser, M., & de Jong, M. D. (2008). Comparing two image research instruments: The Q-sort method versus the Likert attitude questionnaire. *Food quality and preference*, 19(5), 511-518.
- Rathinasabapathi, B. (2004). Survival of *Salmonella* Montevideo on tomato leaves and mature green tomatoes. *Journal of Food Protection*®, 67(10), 2277-2279.
- Rees, C. J., Ngu, W. S., Regula, J., Bisschops, R., Saftoiu, A., Dekker, E., . . . Jover, R. (2016). European Society of Gastrointestinal Endoscopy—Establishing the key unanswered research questions within gastrointestinal endoscopy. *Endoscopy*, 48(10), 884-891.
- Rolfes, L., Kolfschoten, J., Hunsel, F., & Puijenbroek, E. (2016). The validity and reliability of a signal impact assessment tool. *Pharmacoepidemiology and drug safety*.
- Shi, X., Wu, Z., Namvar, A., Kostrzynska, M., Dunfield, K., & Warriner, K. (2009). Microbial population profiles of the microflora associated with pre-and postharvest tomatoes contaminated with *Salmonella typhimurium* or *Salmonella montevideo*. *Journal of applied microbiology*, 107(1), 329-338.
- Soon, J., Davies, W., Chadd, S., & Baines, R. (2012). A Delphi-based approach to developing and validating a farm food safety risk assessment tool by experts. *Expert Systems with Applications*, 39(9), 8325-8336.
- Sullivan, G. M., & Artino Jr, A. R. (2013). Analyzing and interpreting data from Likert-type scales. *Journal of graduate medical education*, 5(4), 541-542.
- US Food and Drug Administration, F. (2008). *Commodity Specific Food Safety Guidelines for the Fresh Tomato Supply Chain*
- US Food and Drug Administration, F. (2015). Standards for the growing, harvesting, packing, and holding of produce for human consumption; Final Rule. *Federal Register Citation: 80 FR, 74353, 74353-74672*.
- Yoshida, S. (2016). Approaches, tools and methods used for setting priorities in health research in the 21st century. *Journal of global health*, 6(1).

9. Figures

Figure 1. (Production flow)

a Large greenhouses: tomato production flow

b Small greenhouses: tomato production flow

Figure 1. Production flow diagram of greenhouse tomato production process in large (a) and small (b) greenhouses.

Figure 2. (Heatmaps)

Figure 2. (Heatmaps) Hierarchical cluster analysis (unsupervised) of raw numerical responses (Likert scale) of participants' expertise self-assessment and years of experience (a) and their opinion on the management practices that could be prioritized to improve food safety in greenhouse tomato production (b). Experienced participants clustering higher in self-reported expertise as expected KS, $P=0.022$ (c), the in responses due to years of experience was not observed KS, $P=0.1616$ (d). The achieved consensus in each module was above 70%, however the agreement varied for each module (e).

9. Tables

Table 1. Participant expertise

Weighted average and percentage of expert participants responding to questions on self-assessment of expertise in knowledge of human pathogens and food safety aspects of fresh produce. The responses with the highest proportions are highlighted.

Scale	Expertise level (% of participants, n=20)					Weighted average
	Minimal 1	Intermediate 2	Advanced 3	Accomplished 4	Expert 5	
Human Pathogen						
<i>Escherichia coli</i>	5.3	26.3	26.3	15.8	26.3	3.32
<i>Salmonella non-typhoid</i>	5.6	22.2	44.4	11.1	16.7	3.11
<i>Listeria monocytogenes</i>	5.3	36.8	21.1	26.3	10.5	3.00
<i>Plant pathogens</i>	36.8	10.5	31.6	5.3	15.8	2.53
<i>Shigella</i> spp.	26.3	47.4	21.1	5.3	0.0	2.05
<i>Noroviruses</i>	36.8	36.8	21.1	5.3	0.0	1.95
<i>Campylobacter</i> spp.	42.1	36.8	21.1	0.0	0.0	1.79
<i>Vibrio</i> spp.	47.4	36.8	10.5	5.3	0.0	1.74
<i>Yersinia enterocolitica</i>	42.1	52.6	5.3	0.0	0.0	1.63
<i>Cryptosporidium parvum</i>	52.6	42.1	5.3	0.0	0.0	1.53
<i>Toxoplasma gondii</i>	57.9	31.6	10.5	0.0	0.0	1.53
<i>Cyclospora cayetanensis</i>	68.4	26.3	5.3	0.0	0.0	1.37
Food Safety in Produce Production						
Fresh vegetables	0.0	15.0	15.0	30.0	40.0	3.95
Tomato	0.0	20.0	25.0	35.0	20.0	3.55
Leafy green vegetables	0.0	21.1	26.3	31.6	21.1	3.53
Fresh fruits	5.3	15.8	26.3	31.6	21.1	3.47
Pre-harvest food safety, vegetables	0.0	5.3	31.6	31.6	31.6	3.89
Pre-harvest food safety, fruits	5.3	21.1	26.3	36.8	10.5	3.26
Post-harvest food safety, vegetables	0.0	21.1	31.6	26.3	21.1	3.47
Post-harvest food safety, fruits	5.3	15.8	42.1	15.8	21.1	3.32
Food safety of GH grown produce	0.0	26.3	52.6	15.8	5.3	3.00
Food safety of field grown produce	0.0	21.1	26.3	36.8	15.8	3.47
Irrigation water (greenhouse)	0.0	36.8	47.4	15.8	0.0	2.79
Irrigation water (field)	0.0	26.3	47.4	21.1	5.3	3.05

Table 2. Priority scores

Delphi expert-based quantification of food safety management practice relevance and prioritization in intensive greenhouse production of tomatoes, based on weighted average responses. Weighted averages are calculated as the sum of the products for each response by the number of participants committed to that answer (in a scale of 1-5) divided by the total number of respondents for each question.

	Participant agreement and quantification of expert responses (% of participants, n=20)					Priority score (Weighted average)
	Agreement	Importance	Low Quartile	Median	Upper Quartile	
Water management						
<i>Testing for human pathogens</i>	73.68	High	4	5	5	3.84
<i>Testing for human path. indicators</i>	73.30	Medium	3	3	4	3.11
<i>Distance of external surface water</i>	80.00	Low	2	2	2	2.33
Worker management practices						
<i>Handwashing</i>	100.00	High	4	5	5	4.67
<i>Enforceable health policy</i>	72.22	High	3	4	5	3.94
<i>Gloves</i>	94.44	High	3	4	4.25	3.78
<i>Restricted visitor access</i>	83.33	High	3	4	5	3.72
<i>Restricted employee access</i>	77.78	High	2.75	4	4.25	3.61
<i>Footbaths</i>	77.78	Medium	2.75	3.5	4.25	3.39
<i>Designated footwear</i>	77.78	Medium	2.75	4	4	3.39
<i>Protective clothing</i>	82.35	Medium	3	4	4	3.33
Environmental controls, surfaces						
<i>Presence of pathogens in environment</i>	84.21	High	4	5	5	4.32
<i>Re-usable plastic containers</i>	88.88	High	3.75	4	5	3.94
<i>Re-used retail-ready packaging</i>	84.21	High	3	4	5	3.89
<i>Utensils and tool (scissors/clippers)</i>	84.2	High	3	4	5	3.74
<i>Greenhouse supplies</i>	84.2	Medium	3	4	4	3.47
<i>Greenhouse equipment</i>	78.94	Medium	3	3	4	3.37
Production practices						
<i>Removing trimmings on the floor</i>	85.71	Medium	2	4	4	3.43
<i>Monitoring for phytopathogens</i>	71.5	Low	1	2	3	2.36
<i>Production bay size</i>	78.57	Low	1	2	3	1.93
<i>Increasing planting density</i>	85.71	Low	1	2	3	1.71
<i>Planting different species (vegetables or ornamentals)</i>	100	Low	1	2	2	1.43
<i>Interplanting*</i>	100	Low	1	2	2	1.43
Presence of animals and insects						
<i>Rodents (mice, rats, voles)</i>	78.95	High	4	4	5	4.26
<i>Birds</i>	84.21	High	4	4	4.25	4.21
<i>Cats</i>	100	High	3	4	5	4.21
<i>Raccoons</i>	70.59	High	3	4	5	4.00
<i>Flies</i>	89.47	High	3	3	4	3.53
<i>Other non-pollinating insects</i>	88.23	Medium	2	3	3	2.82
<i>Pollinating insects (bees)</i>	84.21	Low	1	2	2	1.84
<i>Distance of livestock and poultry operations</i>	73.60	High	3	4	5	3.94
Waste management						
<i>Distance of waste disposal</i>	78.5	High	3	4	4.25	3.78
Traceability						
<i>Traceability to the plant</i>	84.21	High	3	4	5	3.58
<i>Traceability to the picker</i>	78.57	Medium	2	4	4	3.47
Propagation practices						
<i>Employee health and hygiene</i>	100	High	5	5	5	4.87
<i>Mode of irrigation</i>	89.42	High	4	4	5	4.39
<i>Equipment contamination</i>	84.21	High	4	4	5	4.16
<i>Pesticide application</i>	50.00*	Medium	2	3	4	3.39
<i>Seed contamination</i>	52.63**	Medium	2	3	4	3.26

<i>Propagation of multiple vegetable species</i>	100	Low	1	1.5	2	2.16
<i>propagation of ornamentals</i>	100	Low	1	1.5	2	2.11

* The stability of the responses was determined based on 4.5% change
**The stability of the response was determined based on 5% change

Table 3. Need for expanded and new management practices to ensure food safety in greenhouse tomato production

Management Practices
Currently practiced
Pest control (rodents, other animals and insects except of cats)
Environmental control (sanitation of clippers/scissors)
Inadequately practiced
Handwashing
Gloves
Restricted visitor access
Restricted employee access
Footbaths
Designated footwear
Protective clothing
Removing trimmings under troughs
Recommended, but not practiced*
Testing for human pathogens
Testing for human pathogen indicators
Traceability to the plant
Traceability to the picker
Pest control (cats)
Environmental control (sanitation of all contact and environmental surfaces other than scissors/clippers)
Propagation controls