Improving fresh produce safety: Application of UV tunnel technology and visual educational tools

by

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Abstract

Fresh produce is an important component of the human diet, and about 50% of the total fresh produce consumed in the US is domestically produced. Immigrants and refugees form a large part of the workforce in this industry, accounting for nearly 70% of all workers. Despite this reliance, most non-English-speaking growers struggle to learn and follow produce safety practices. This issue is further complicated due to a lack of relevant training materials tailored to different cultures and languages.

To address this gap, visual educational materials for non-English-speaking growers were developed and evaluated in this study. A needs assessment with Iowa and Kansas refugee growers was conducted and involved feedback from extension personnel and community organizations. This assessment identified four critical areas of food safety knowledge: (1) workers' health and sickness symptoms, (2) visitor management on produce farms, (3) contamination on produce farms through animals, and (4) appropriate application of Biological Soil Amendments of Animal Origins (BSAAOs). The ADDIE (Analysis, Design, Development, Implementation, and Evaluation) Design-Based Research framework was used to design four multilingual produce safety posters in Swahili, Burmese, Kirundi, and Nepali. The posters had animated, and culturally meaningful visuals based on the Produce Safety Rule. An evaluation was done with 26 growers using a pre-post-test design that relied on the Theory of Planned Behavior (TPB). All TPB constructs significantly improved after the poster intervention, with the largest gains observed in Perceived Behavioral Control (PBC) and intention, with statistically and practically significant improvements. The strong correlation between PBC, attitude, and intention demonstrated that posters had a strong positive effect on growers' motivation to act, indicating that visual materials helped to improve produce safety awareness.

In addition to the educational barriers, another critical issue in the fresh produce industry is the lack of an effective decontamination strategy for root vegetables, with reliance on traditional dip-washing using sanitizers. This results in a lack of effective decontamination due to organic load, surface texture, irregularities, and restrictions on using high concentrations of chemicals on fresh produce. These limitations can be overcome by the application of UV light or their combined application with effective chemical sanitizers.

To address this gap, a study was conducted to determine the effectiveness of a novel decontamination tunnel system to reduce *Escherichia coli* contamination on whole carrots. The experiment used four groups: control, UV-C, Peracetic Acid (PAA), and combined treatment UV-C and PAA, and was repeated in three trials. The study revealed that the highest mean microbial reduction (2.83 ± 0.10 log CFU/g) was found with the combination of PAA and UV-C, and this was significantly greater than PAA (2.38 ± 0.06 log CFU/g) and UV-C alone (1.49 ± 0.16 log CFU/g) ($p < 0.0001$). Such a complementary effect of UV-C and PAA illustrates superior effectiveness for root vegetable decontamination.

By empowering underserved groups with culturally sensitive educational resources and by advancing decontamination strategies through innovative postharvest interventions, the scientific findings reported in this thesis work have practical relevance in ensuring improved microbial safety of fresh produce in the U.S.

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Chapter 1 - Visual Educational Resources to Improve Produce Safety Knowledge for Non-English-Speaking Farm Workers in the U.S.: A Review

Abstract

The U.S. produces 50% of its total fresh fruits and vegetables consumption. Labor, one of the key inputs to fresh produce production, is required to conduct field activities such as planting and harvesting. To meet this demand of the U.S., the produce industry depends significantly on immigrant workers, who make up almost 70% of the workforce of the world's third-largest fresh produce sector. Fresh produce is also implicated in foodborne outbreaks. One of the factors limiting effective food safety implementation on farms is the lack of education and training. Specific to non-English-speaking immigrant workers, this challenge presents a significant obstacle in training the farm workforce and maintaining safety standards in this industry. This article discusses key issues of food safety practices within the fresh produce industry that require improved training of farm workers, particularly focusing on the development of needs-based visual educational resources, such as videos and posters, for non-English-speaking immigrant growers. It also discusses addressing those gaps by delivering tailored educational resources and the potential impact on improved transfer of knowledge.

Keywords: Foodborne outbreaks, Fresh Produce, Food Safety, Immigrants, Visual Educational Resources

Introduction

Despite the United States (U.S.) being the third-largest producer of fresh fruits and vegetables in the world (Shahbandeh, 2024), this industry faces a persistent challenge: foodborne illnesses linked to contaminated fresh produce. With nearly 70% of fresh vegetables and about 45% of fresh fruits consumed in the U.S. being domestically grown, the stakes are high for public health and the economy (Ribera & Young, 2024). The U.S. Centers for Disease Control and Prevention (CDC) estimated that around 46 percent of foodborne illness outbreaks result from fresh produce and nuts, and safety measures remain a critical issue in the supply chain (CDC, 2025).

The U.S. fresh produce industry heavily depends on immigrant and refugee labor, with most of them from non-English-speaking backgrounds (National Agricultural Workers Survey, 2018). The Food Safety Modernization Act (FSMA) Produce Safety Rule (PSR) was released in November 2015, and it defines the minimum standards for various farm activities like growing, harvesting, packing, and holding of fresh produce used in direct human consumption (without processing) (United States Food and Drug Administration, 2015). The Produce Safety Alliance (PSA) is an educational partnership between the Food and Drug Administration (FDA), the United States Department of Agriculture (USDA), and Cornell University to train fresh produce growers about the minimum requirements included in the FSMA PSR. The training aims to mitigate microbial contamination risks in the fresh produce supply chain and assist growers to comply with the regulation. However, these efforts are lacking among non-English-speaking farmworkers and growers, where training curricula are mostly in English. Since immigrant workers are a major source of the workforce in the agriculture industry of the U.S., it is crucial to fill this educational gap to sustain the credibility of the fresh produce chain. This gap can be bridged by developing training materials such as visual education aids, videos, and posters to ensure that those educational resources are clear, culturally appropriate, and easily understood (Balis et al., 2019).

This literature review looks at the challenges faced by immigrant fresh produce growers and farm workers in the U.S. who don't speak English. It focuses on factors that cause fresh produce outbreaks, the current food safety regulations, and the obstacles to food safety education. The review also discusses the educational resources that could help the non-English-speaking workforce on fresh produce farms while intending to offer ideas for improving food safety education.

Fresh Produce Outbreaks and Foodborne Illness in the U.S.

According to the World Health Organization (WHO), globally, approximately 600 million people become sick due to foodborne illness, and 420,000 die each year (WHO, 2016). The CDC defines an outbreak as a situation where two or more individuals get sick with the same illness after eating the same type of food (CDC, 2022). In the U.S., the CDC and the FDA play crucial roles in investigating and responding to foodborne outbreaks (CDC, 2024). The FDA and the U.S. Department of Agriculture's Food Safety and Inspection Service (USDA-FSIS) mandate food recalls (Qiu et al., 2021). Foodborne illness estimations from the CDC reveal that around 48 million people become sick due to foodborne pathogens every year in the U.S.; out of these, 128,000 individuals get hospitalized, and nearly 3,000 individuals lose their lives (CDC, 2018).

With high per capita consumption of fresh produce like vegetables and fruits in the U.S. (Statista, 2024), foodborne illnesses from contaminated produce are very likely, especially when consumed raw (Machado-Moreira et al., 2019). The key pathogens causing foodborne illnesses through contaminated fresh produce include *Salmonella* (43.1%), *Escherichia coli* (68.8%), and *Listeria* (51.1%) (CDC, 2023a). Different fresh produce, such as tomatoes, sprouts, leafy greens, and cantaloupes, is associated with a high risk of foodborne outbreaks. Foodborne outbreaks from fresh produce are recurrent despite efforts to prevent them. Leafy greens are one of the most common food vehicles for contamination through *E. coli* and *Listeria*. In 2021, the CDC investigated 74 possible multistate outbreaks, out of which 47 (64%) had their sources identified. Among these solved outbreaks, 28 (60%) were due to contaminated food, while the remaining 40% were due to contact with animals (CDC, 2023b). Among all the cases examined, just 25 outbreaks had a confirmed source, with five outbreaks linked to leafy greens and one associated with underground or root vegetables. Notably, the latter was responsible for the highest number of illnesses reported in solved foodborne outbreaks, totaling 1,040 cases.

Common Causes of Fresh Produce Outbreaks

Fresh produce can be contaminated with different foodborne pathogens, which pose a risk to public health, and this contamination can occur throughout different stages, including production, harvesting, processing, packaging, and distribution. Biological contamination of fresh produce on farms is a particular concern, where pathogens like *E. coli*, *Salmonella*, *Campylobacter*, *L. monocytogenes*, and *Arcobacter* are commonly found in manure, agricultural water, and compost (Ferguson et al., 2023). Some of the common causes of contamination on farms are Biological Soil Amendments of Animal Origin (BSAAOs), improper hygiene from workers and visitors, and sick workers working on the farms.

Biological Soil Amendments of Animal Origin (BSAAOs)

BSAAOs, including manure, compost, poultry litter, and biosolids, enhance soil quality but may introduce microorganisms such as *E. coli*, *Salmonella*, *and Listeria* as well as parasites like Cryptosporidium and Toxoplasma to soil and produce crops (Delahoy et al., 2018; Heredia & García, 2018). *Salmonella*, *E. coli*, and *Listeria* are related to different types of BSAAOs in that fresh manure poses a more significant threat than composted manure (Alegbeleye et al., 2018; Black et al., 2021; Lemunier et al., 2005). Manure from animals, including cattle, swine, and poultry, may contain pathogens such as *E. coli*, *Salmonella*, and *L. monocytogenes,* and raw, untreated, and improperly stored or applied manure is more likely to transfer pathogenic to produce crops than composted materials (Black et al., 2021; Gurtler et al., 2018; Love et al., 2012).

The foodborne pathogens present in both soil and fresh produce growing in the soil treated with BSAAOs significantly decrease when the current National Organic Program (NOP) wait-time of 90-120 days is implemented, reiterating how safe food practices on the farm can ensure fresh produce safety (Ramos et al., 2021). These wait times cover the fact that different crops may become more or less susceptible to microbial contamination depending on factors such as the surface of the produce, its proximity to the ground, and the method by which it was harvested (Mritunjay & Kumar, 2017; Park et al., 2012; Runkel, 2022). Leafy greens, berries, and root crops are prone to contamination by these pathogens because of their complex structure, highly developed canopy, as well as their contact with the ground. On the other hand, vegetables that are less likely to be affected are those with hard external cover, for instance, bell peppers and cucumbers, because they are less rough, grow above ground, and have a simpler structure (Alegbeleye et al., 2018).

Hygiene (Workers and Visitors)

In fresh produce farms, there is the risk of contamination by various people, which may include workers and visitors. The FSMA PSR emphasizes providing information to the visitor about the food safety policies on the farm, the provision of adequate facilities like handwashing stations and restrooms for personal hygiene, and proper management of visitor access to food contact zones in the farm (United States Food and Drug Administration, 2015). Contamination can occur through infected workers handling produce on the farm and through contaminated workers' clothes if the workers do not implement hygiene measures (Gorgo-Gourovitch et al., 2019).

Farm workers working with dirty hands can also become a source of pathogens, which can contaminate fresh produce if the farm workers are involved in the harvesting, handling, and packaging processes. Illnesses can also be caused by pathogens like norovirus, hepatitis A, and *Shigella*, which may be contracted through direct contact if farm workers do not wash their hands (O'Shea et al., 2019). Moreover, workers touching food contact surfaces, equipment, or harvested produce with contaminated hands can lead to the further spread of pathogens. Handwashing is the main weapon in reducing such microbes from hands so that the risk of contamination of produce or transmission to others is decreased. Hands should be washed after using the restroom, coughing, sneezing, before and after eating foods, and handling soiled or dirty tools, equipment, work surfaces, and after handling garbage (Bihn & Gravani, 2005).

Worker Health

The health status of a farm worker is critical in preventing the microbial contamination of fresh produce. If sick or injured workers handle produce crops, they may introduce pathogens through contact with produce, respiratory secretions, or bodily fluids (Produce Safety Alliance, 2019). So, it is important to identify symptoms that can result in contamination and pose a threat to public health (Nordgren & Charavaryamath, 2018). To prevent this risk, workers who have any symptoms like fever, diarrhea, stomach pain, jaundice, vomiting, or other symptoms of foodborne pathogens must immediately notify the farm supervisor. Such workers are best to stay home until they are symptom-free, but they must not handle fresh produce if they must be at the farm for some reason. Moreover, if workers have open sores or boils, they should also be prohibited from handling the produce directly. In case of an injury, first aid kits should also be available in a convenient location within the working areas on the farm, and they should be monitored monthly to ensure that they are properly stocked (Gorgo-Gourovitch et al., 2019).

Fresh Produce Safety Regulations in the U.S.

The FSMA PSR was developed to protect fresh produce by ensuring proper identification and management of biological risks from poor agricultural practices, food safety ignorance among growers, and various hazards on farms (Singh Bhullar et al., 2019; Yin et al., 2022). Specific guidelines for the application of compost and manure for organic farmers to comply with the organic certification are offered by the National Organic Program (NOP) for organic farms (National Organic Program, 2010). This guideline is also recommended for non-organic growers as well as growers who use untreated animal manure on their farms.

However, within the FSMA Produce Safety Rule, there are exemptions: producers who operate on a small scale and supply locally in a 275-mile radius/inside the local state or same Indian reservation and consistently make under $25,000 in total produce sales annually for 3 years, adjusted for inflation, are exempt from the rule (United States Food and Drug Administration, 2015). This results in smaller producers often having little to no knowledge of food safety standards and no governmental inspection of their fresh produce safety practices (Beecher, 2013). Small-scale growers, especially the ones who also work with domestic or wild animals close to produce growing areas, need to understand the intricate and diverse ways in which microbial contamination can occur (Marine et al., 2016).

Immigrant and Refugee Farm Workers/Growers in the U.S.

Immigrants are a huge part of the U.S. population, and they contribute greatly to its economy. About 13.7 percent of the total population, or about 44.9 million immigrants, were in the U.S. in 2018. Over the years, immigration trends have changed, with the immigrant population increasing from 9.6 million in 1970 to 44.9 million in 2018. Mexico is the largest country of origin, accounting for 24 percent of the total, succeeding India (6%), China (5%), the Philippines (4.5%), and El Salvador (3%); the immigration trend shows a growing number of African and Asian immigrants in recent years (American Immigration Council, 2021).

More than three-quarters of the 2.4 million farm laborers are immigrants, and the farming industry in the U.S. is heavily dependent on immigrant workers. So, it becomes important that our immigrant farm workers are properly aware of proper food safety measures while working on the farm (Cheney et al., 2022). Nearly 258,000 immigrants received H-2A visas as agricultural workers just in the year 2019; however, more than double the number of these immigrant workers are in the U.S., working as unauthorized immigrants. These workers, distributed throughout various states in the U.S., are so critical that the estimation of the fall of agricultural output if foreign-born workers are to be lost is 30-60 billion in the dairy industry alone (FWD.US, 2022).

In the U.S., the refugee population is also growing fresh produce, particularly in urban areas. Refugees have long been resettled in the U.S., with thousands of people arriving at the U.S. border or already in the country seeking asylum each year (Hinterlang, 2024; Nicole Ward & Jeanne Batalova, 2023). The U.S. Refugee Admissions Program allows refugees to be admitted to the U.S., with allocation through the family preference system. Midwestern states have always welcomed refugees from Africa and Southeast Asia who speak various languages (Arena & Wheaton, 2021). Most of these refugee populations prefer agriculture as a preferred occupation because it offers opportunities for placemaking, longer-term integration, and control of the food supply (Foss et al., 2024). In the U.S., refugees often return to their primary occupation, farming, with assistance from non-governmental organizations in community gardens or training garden plots (Fetahovic, 2020; Goralnik et al., 2023; Jarman, 2021).

Fresh Produce Safety Education: Gaps and Barriers

Reducing fresh produce contamination and the resulting foodborne illnesses requires educational resources on fresh produce safety. In response to this need, the PSA has taken the initiative and introduced training programs like the FSMAPSA Grower Training Course and Train-the-Trainer Course, both to educate produce safety educators as well as to help fresh produce growers learn about safety practices. In Pennsylvania, community-tailored efforts have produced educational materials and provided training to Latino Fresh Produce Growers and Farmworkers (Penn State, 2021). The Kansas Department of Agriculture (2021) also provides resources for food safety, from food safety information to information about farmers' markets and consumer safety. Assessments of Midwest growers' needs to comply with the PSR have led to the development of educational materials tailored to the specific challenges faced by fresh produce growers in the region (B. Perry et al., 2019).

However, with PSA Grower training courses available in just five languages, including English, and most of the other educational resources developed mainly for English-speaking audiences, communication challenges for other non-English-speaking farm workers or growers in the U.S. are a major challenge (Esmaeili et al., 2014). Language difficulties, along with cultural differences, make traditional educational resources less accessible and understandable for non-English-speaking growers. Among a few key problems in ensuring food safety on produce farms is the lack of written food safety plans, financial resources, farm infrastructure, and language barriers (B. J. Perry et al., 2021). Non-English-speaking farming communities may struggle to understand food safety programs, resources, and policies, with food safety not being a critical part of their traditional farming approach in their native countries (United States Department of Agriculture, 2023). Additionally, cultural differences and limited schooling result in a lack of foundational knowledge of key food safety measures for underserved populations, including migrant workers and refugees (Nisbet et al., 2022).

Languages other than English can be used to provide information related to food safety practices to help remove language barriers and to communicate more effectively with non-English speaking audiences. This was demonstrated to improve the food safety practices of food workers who used culturally appropriate training materials, and it is suggested that such training programs be evaluated through the feedback of the target population. If standardized materials contain pictures or examples of culturally different target populations, it is important to address their differences while designing interventions for culturally diverse communities. It is often necessary to modify educational material, and in doing so, it is important to consider the cultural differences of the audience, and the pictures and examples provided in standardized materials (Rajagopal, 2012; Strohbehn et al., 2018).

Preferred Educational Resources for Non-English-Speaking Farm Workers/Growers

Customized educational materials specifically targeting the needs of immigrant farm workers and growers in the U.S. provide benefits to immigrant farm workers and growers. It is possible to overcome the barriers they face and help them produce safe and healthy food with better outcomes by tailoring the resources to their requirements (Enderton et al., 2023). To better address the fresh produce safety needs of this audience in the U.S., educational programming should be developed based on factors such as farm size, region, market access, and farm type. With workshops and partnerships with local agriculture extension services, this approach, combined with the training provided, would ensure that the training given is relevant and specific to the circumstances of their work environment (B. Perry et al., 2019; Snellman, 2013).

Over the past few years, it has been increasingly found that the use of visual educational resources has been more effective at engaging and educating individuals about promoting healthy behaviors like safe food handling practices versus traditional text-based resources. The use of visual educational resources was found effective in improving participants' knowledge and behavior related to fresh produce safety (Kang et al., 2015). Infographics and videos are especially useful in helping to convey information regarding fresh produce safety. These resources must; however, be designed in a way that will resonate with the reality of the target audience’s workplace settings. Also, technical terms should be avoided in favor of everyday terms readily understood by the non-English speaking audience (Mathiasen et al., 2012).

Posters have also been acknowledged as an efficacious educational tool due to their ability to convey complex information through visual imagery in a passively delivered educational intervention (Chapman et al., 2010; Dworkin et al., 2012; Rajagopal et al., 2019). Posters developed for safe handling practices of leafy greens in food service operations in Iowa and Kansas have shown positive impacts not only on the food safety behaviors of the workers but also on the microbial contamination level of the leafy greens (Rajagopal et al., 2016). Hand hygiene educational posters tailored to the needs of agricultural growers who do not understand English are seen to have a positive impact on their handwashing practices and understanding (Soon & Baines, 2012). Food safety training can be improved by incorporating such posters for communicating food safety messages across a wide range of produce growers. More research into this area needs to be conducted to explore the capacity of visual educational resources to promote fresh produce safety practices.

Theory of Planned Behavior

The Theory of Planned Behavior (TPB), which was developed by Icek Ajzen (1985), predicts human behavior based on intentions influenced by three factors: personal attitudes, subjective norms, and perceived behavioral control.

Personal attitudes represent an individual's positive or negative evaluation of performing a particular behavior based on beliefs about the potential outcomes. For example, a grower considering adopting proper handwashing techniques may believe that this behavior will reduce the risk of contamination. If the grower values the health and safety of their consumers, they are likely to develop a positive attitude toward implementing this safety practice. Attitudes are often measured through surveys where individuals rate their agreement with statements about the anticipated outcomes and desirability of the behavior.

Subjective norms involve the perceived social pressure from important others, such as family, colleagues, supervisors, or industry standards, regarding whether to perform or refrain from a behavior. This factor is influenced by normative beliefs about the expectations of these key individuals and the individual's motivation to comply with these expectations. For instance, if a grower perceives that their supervisor expects them to use proper sanitization methods, they are more likely to adopt these practices. Subjective norms are typically assessed by asking individuals how much they feel influenced by others and who they think would approve or disapprove of their actions.

Perceived behavioral control refers to an individual's belief in their ability to perform the behavior, encompassing the perceived ease or difficulty of performing the behavior and their confidence in their ability to do so. This factor is linked to the presence of factors that may facilitate or hinder the performance of the behavior. For example, a grower may feel hesitant to implement proper handwashing protocols if they perceive a lack of adequate facilities or resources on their farm. However, if they believe that they have access to necessary resources, such as handwashing stations, their perceived control over adopting this practice increases. Perceived behavioral control is often measured by asking individuals to rate how much control they feel they have over adopting the behavior and their confidence in their ability to execute it under various circumstances.

This theory has been extensively utilized in various studies related to food safety education and interventions. It has proven to be a valuable framework for designing educational resources and interventions aimed at promoting safe food handling practices, including those related to fresh produce safety. Moreover, the application of the TPB has extended beyond traditional food safety topics. Previously, in the context of fresh produce safety, researchers have used the TPB to design interventions and educational resources aimed at promoting food hygiene practices (Archila-Godínez et al., 2022; Arvola et al., 2008; Nickell & Hinsz, 2023).

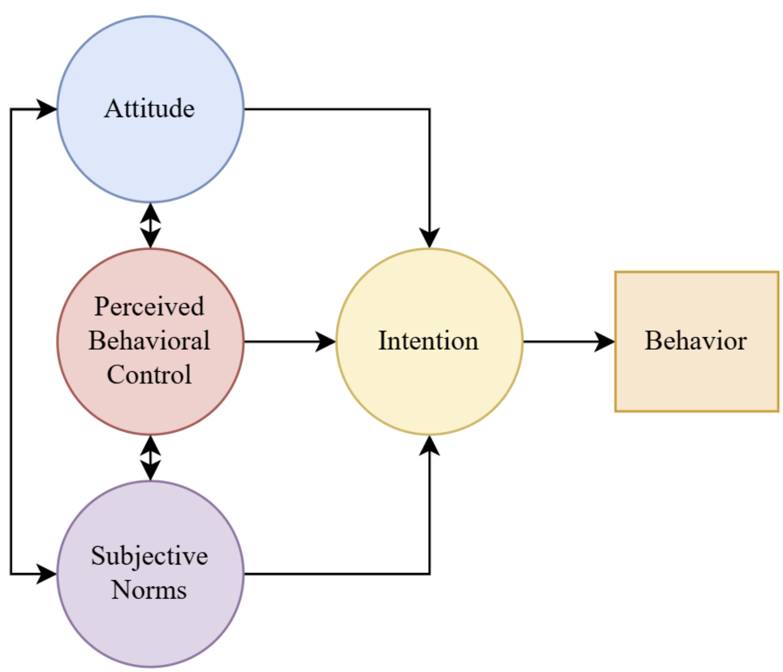

Figure 1.1. Theory of Planned Behavior (Ajzen, 1991)

The theory of planned behavior and the use of visual educational resources are both valuable tools in promoting safe food handling practices, including those related to fresh produce safety. By understanding the factors that influence individuals' intentions and behaviors, educators and researchers can develop effective strategies to improve food safety practices among various populations.

Contribution to the Urban Food System

The aim of this research is to enhance the development of resilient and inclusive food systems in urban and peri-urban areas by focusing on multiple aspects of enhancing the microbial safety status of fresh produce. Urban food systems are highly interconnected systems of production, distribution, and consumption with multiple stakeholders, including refugee and immigrant produce growers, who play a pivotal role in producing locally grown fruits and vegetables for nearby urban cities, which is especially true for urban areas of Midwest cities like Kansas City. However, inadequate food safety information and the unavailability of culturally relevant education materials among producers pose a threat to the uncertainty of safe practices on farms.

To address these issues, the current study seeks to develop multilingual and culturally sensitive visual educational materials. These resources are meant to empower growers who do not speak English by raising their awareness of safe produce practices and, by doing this, reducing microbial contamination risk from the source. This effort is particularly significant in local markets, Community-Supported Agriculture (CSA) networks, and farm-to-school programs depending on small and mid-sized urban growers. In addition, the posters also tackle literacy and language concerns, enhancing food safety training accessibility in urban agriculture that may be limited by access to regular training.

In addition to these educational resources, the laboratory component of the research compares scalable, decontamination technologies using a novel decontamination tunnel. Urban farms do not generally possess industrial-scale sanitizers; therefore, the proposed tunnel system with added UV and sanitizer treatments is a viable postharvest intervention appropriate for small-scale operations characteristic of urban agriculture. This makes it possible to attain urban sustainability goals as well as environmentally friendly production by reducing chemical use.

Conclusion

In conclusion, foodborne outbreaks are a huge concern in the U.S. because of their huge negative effect on public health and the economy. Immigrant farm workers and growers, who are a large part of the fresh produce industry, continue to lack sufficient educational resources in their language and culture to understand current fresh produce safety measures. This gap, discussed in this review, needs to be filled with additional educational resources, such as visual aids, to help with comprehension and retention. More research into visual teaching materials like videos and posters in the fresh produce industry could be a good way to increase the use of visual aids in education for a wide range of groups. To help this non-English speaking audience learn more about food safety, materials that are both visually appealing and relevant to their culture should be included. These materials should be used in agricultural extension programs and food safety training programs. This approach can result in better communication and education across non-tradition and non-English-speaking growers to implement better food safety practices. Future work should create such visual education resources and evaluate the efficacy of videos and posters in increasing farm workers' and produce growers' knowledge.

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Chapter 2 - Developing and Evaluating Produce Safety Posters as an Effective Educational Tool

Abstract

Immigrant and refugee fresh produce growers are often unfamiliar with the fresh produce safety practices in the U.S. This unfamiliarity could pose a threat to public health, as not following proper food safety practices could lead to contamination events and foodborne outbreaks. Most current food safety educational resources, primarily oriented toward English-speaking growers, rely heavily on complex scientific language and therefore fail to resonate and have a meaningful impact among growers who come from limited educational backgrounds. Visually driven and culturally appropriate resources are important to overcome the existing linguistic and cultural barriers in food safety education of such growers, so four multilingual produce-safety posters were developed using an integrated ADDIE Design-Based Research Approach. A needs assessment conducted with input from 10 refugee growers in Iowa and Kansas through focus-group sessions and interviews, farm visits, and feedback from an advisory board led to identifying four critical areas of concern in produce safety knowledge. Based on identified topics, visually engaging, informative, and culturally and contextually appropriate posters were developed. After the development of the posters, a pre-post evaluation (n=26) was conducted to measure the impact of these posters based on the Theory of Planned Behavior (TPB). All Theory of Planned Behavior (TPB) constructs showed statistically significant improvements ($p<0.05$) across the intervention of all four produce safety posters, with the biggest improvement observed in Perceived Behavioral Control (PBC) and Intention. Specifically, the PBC improved by 0.38 to 0.47 points and intention by 0.28 to 0.51 points across four poster measurements on a four-point scale. These improvements were not only statistically significant but also practically meaningful, with Cohen's d effect sizes ranging from 0.86 to 1.14 for PBC and 0.94 to 1.21 for Intention, both representing large effects. In addition, a strong relationship between PBC and intention (r = 0.81 to 0.87), as well as between PBC and attitude (r = 0.74 to 0.84), was observed. These findings suggest that using visual education resources can be a great tool for training to enhance knowledge gains and improve attitudes and intentions of produce growers to implement better produce safety practices.

Keywords: Produce safety; Refugee growers; Visual educational resources; Produce Safety Posters; Theory of Planned Behavior (TPB)

Introduction

According to World Health Organization (WHO) research, foodborne outbreaks affect approximately 600 million people annually worldwide, resulting in an estimated 420,000 deaths. In the global population, unsafe food is estimated to cause illness to approximately every 10th person (WHO, 2024), and it is estimated to annually affect one-sixth of Americans (CDC, 2023). In 2023, the FoodNet surveillance system by the US Centers for Disease Control and Prevention (CDC) revealed 29,607 laboratory-confirmed foodborne illness cases, including 7234 hospitalizations and 177 deaths among approximately 15% of the US population, which is covered under the surveillance network (Shah et al., 2024). More than half of the produce consumed in the US is produced domestically, as the US imports 41.2% of the produce consumed in the US (Ribera & Young, 2024).

Poor food safety management practices at fresh produce farms have frequently been identified as a significant source of contamination during the investigation of various foodborne outbreaks. In the U.S., one of the deadliest outbreaks in recent years was caused by *Listeria monocytogenes*, which contaminated cantaloupe consumed across 28 states, leading to the disease Listeriosis, resulting in 33 deaths and a miscarriage. This deadly event was traced back to Jensen Farms in Colorado, which led to the recall of 300,000 cantaloupes (McCollum et al., 2013). The number of reported outbreaks related to the "fresh produce" food category has rapidly increased over the last few decades. During the 1970s, produce-related outbreaks represented 0.7% of all food item outbreaks that had been identified. The 1990s saw a noticeable increase in produce-related outbreaks in the US, reaching 6% (Sivapalasingam et al., 2004). This number increased 8% during 1998-2001 and 16% during 2010-2013 (Bennett et al., 2018). Foodborne illness investigations from 1998 to 2008 identified six plant categories to be the likely cause of 46% of reported illnesses, which included fruits-nuts, fungi-vegetables, leafy vegetables, root vegetables, sprout vegetables, and vine stalk vegetables (Painter et al., 2013). These data emphasize the increasing risks of foodborne outbreaks associated with fresh produce and the critical role of good food safety practices at produce farms in such outbreaks.

Although there have been substantial improvements in produce safety education, including the establishment of the Produce Safety Alliance (PSA) that provides extensive training and Spanish-language resources to immigrant farmworkers (Produce Safety Alliance, 2019), not every grower community gets equal access to the resources. Most of the current training is tailored towards large-scale farm enterprises, in which immigrant farmworkers are usually trained to perform specific tasks under the guidance of farm managers who oversee food safety.

Contrastingly, the target population of this project is mainly refugee and resettled immigrant growers who run small-scale urban farm plots, many of which are communal. These are not employees but rather independent operators who do all the farming activities themselves, including soil preparation, harvest, and postharvest handling, and in many cases, without regulatory oversight. A lot of these independent operators/growers do not speak Spanish, and their languages are Swahili, Karen, Somali, Nepali, Chin, Burmese, Falam, and many others, where there is a shortage of accessible produce safety resources (Jarman, 2021).

Despite the useful development of Spanish-language resources, there is still a major gap with non-Spanish-speaking, low-literacy refugee growers whose products are becoming part of local food systems in the form of farmers markets and community-supported agriculture. In the absence of materials that are linguistically, culturally, and educationally relevant, these growers are unable to adopt the best produce safety practices that ensure microbial safety of their produce crops. Lack of food safety knowledge and educational resources has been identified as a major barrier to compliance with produce safety practices among growers (Chen et al., 2021). Education plays a crucial role in mitigating these risks by equipping growers and farmworkers with the knowledge and practices necessary to minimize contamination. However, barriers to effective education persist, particularly among non-English-speaking and low-literacy populations, who may struggle to access or comprehend traditional food safety training materials (Fox, 2020; Parker et al., 2012). These challenges are further compounded for refugee and immigrant growers, who often face additional cultural and linguistic barriers that hinder their ability to adopt recommended food safety practices (Aning, 2023).

One of the primary barriers to food safety education is the overwhelming amount of information presented in formats that are not accessible to all growers (Bianco et al., 2016; Neal et al., 2011). Many educational programs are designed for English-speaking audiences and heavily rely on written materials, which may not be effective for individuals with limited literacy or unfamiliarity with the concepts (Arena & Wheaton, 2021; Dunlap et al., 2016; Fetahovic, 2020). This is particularly problematic for non-English-speaking growers, who may lack proficiency in English and come from countries with agricultural practices and food safety regulations that differ significantly from those in the United States (Nabwiire et al., 2021). To address these challenges, education programs need to be tailored to the specific needs of these populations by incorporating more visually based training and materials in their native languages. Videos, images, and hands-on demonstrations can be more effective than text-heavy manuals as they provide clearer, actionable guidance that transcends language barriers (Li et al., 2015; Rajagopal, 2012, 2013; Rajagopal et al., 2019).

Moreover, the effectiveness of food safety education is often influenced by the cultural context and prior experiences of the learners. Refugee and immigrant growers may have different approaches to farming based on agricultural practices from their home countries (Goralnik et al., 2023). It is essential for educators to acknowledge these cultural differences and develop programs that resonate with learners' experiences, while also emphasizing the importance of U.S. food safety regulations. By addressing these barriers and customizing education to the unique needs of diverse grower populations, food safety training can become more inclusive and effective, ultimately reducing the risk of contamination in the fresh produce supply chain.

Problem Statement

Non-English-speaking immigrants with refugee backgrounds make up a substantial part of the Midwest US workforce, contributing to performing various activities on fresh produce farms. Workers from diverse backgrounds who participate extensively in local food systems encounter multiple barriers, including language differences, cultural variations, and food safety literacy problems. Refugees in states like Kansas and Missouri have been resettled through social service institutions, dating back to agricultural support structures such as the Global Greens and New Roots for Refugees programs (Fetahovic, 2020). However, many immigrants originating from non-English-speaking backgrounds often lack access to culturally relevant educational resources intended to enhance their understanding of food safety regulations and best practices in fresh produce production (Jarman, 2021).

The difficulties faced by immigrants are heightened by inadequate visual educational resources, as available materials primarily use textual content. To address these issues, there is a need to create visual educational resources that acknowledge linguistic differences while providing relevant content for refugee and immigrant growers who represent diverse cultural backgrounds. The research aims to develop specific visual educational materials for fresh produce safety education, increasing knowledge and safety practices among vulnerable populations while advancing safer food production systems at the local level.

Research Objectives

The long-term goal of this project was to ensure access to relevant educational resources on fresh produce safety for refugee growers in the Midwest. The information included in these resources is essential for helping refugee growers understand and identify potential food safety hazards, for which they need to develop preventive measures to grow safe food. The resources include problem-centered and real-world scenarios, providing the growers with broad knowledge of proper food safety practices and an understanding of when, where, and how to implement their new knowledge. This was achieved by following specific objectives:

1) Conduct needs assessments to identify the gaps in produce safety knowledge and practices for non-English-speaking immigrant growers in Iowa and Kansas
2) Develop posters in the native languages of and with appropriate contexts for non-English-speaking immigrant growers in Iowa and Kansas
3) Evaluate the curriculum outcomes by conducting a survey assessment of growers' attitudes, perceived behavioral control, subjective norms, and anticipated behavior after viewing the posters.

Methodology

Research Design

To effectively address the unique challenges faced by non-English-speaking immigrant growers, this study combines the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model (Mayfield, 2011; Shibley et al., 2011) with the Design-Based Research (DBR) approach (Anderson & Shattuck, 2012; Baumgartner et al., 2003). The ADDIE model provides a structured framework for developing educational materials through systematic phases, ensuring that the final resources are grounded in both theoretical and practical principles. Meanwhile, the DBR approach allows for an iterative design process, emphasizing continuous refinement of the educational resources based on feedback from the advisory board members, including food safety experts, refugee growers, and members from organizations that assist non-English-speaking growers in farming in the U.S., thus ensuring that the materials are contextually and culturally relevant.

ADDIE Model

The ADDIE model, a systematic instructional design framework comprising Analysis, Design, Development, Implementation, and Evaluation, offers a structured approach to creating effective training resources (Cotter et al., 2023), including fresh produce safety posters. In the analysis phase, the learner needs and contextual factors are identified, such as understanding growers' knowledge gaps and regulatory requirements. During the design phase, learning objectives are translated into visual and textual strategies, determining poster layout, key messages, and visual aids to maximize clarity and engagement. The development phase involves crafting posters, integrating visuals like icons or infographics, and ensuring content aligns with safety standards while remaining accessible. The implementation phase focuses on strategic intervention using the developed resources as educational references. Finally, evaluation assesses effectiveness through user feedback, behavioral observations, or knowledge assessments, enabling iterative refinements to enhance relevance and impact.

DBR Approach

Design-Based Research (DBR) is an iterative process of designing and developing practice-based learning interventions. It is well-suited to projects like producing safety poster designs because it focuses strongly on both practical and theoretical outputs (Baumgartner et al., 2003). DBR begins by identifying real-world problems, such as language issues or low literacy levels among non-English-speaking farmers and then researches these issues through practitioners and community members (Barab & Squire, 2004). Researchers develop and design the first prototypes based on that research, incorporating visual strategies that align with the learning goals. The prototypes are then tested in naturalistic environments, such as farms, and the researchers observe how individuals use the materials and their opinions on developed resources. Ongoing feedback from stakeholders with the same knowledge and experience ensures that the intervention remains practical, contextually relevant, and user-need compatible, with the potential for ongoing refinement in the design process (T. Anderson & Shattuck, 2012). Lastly, DBR not only leads to improved materials but also adds to the principles that may be used in guiding subsequent instructional interventions in similar contexts (Baumgartner et al., 2003).

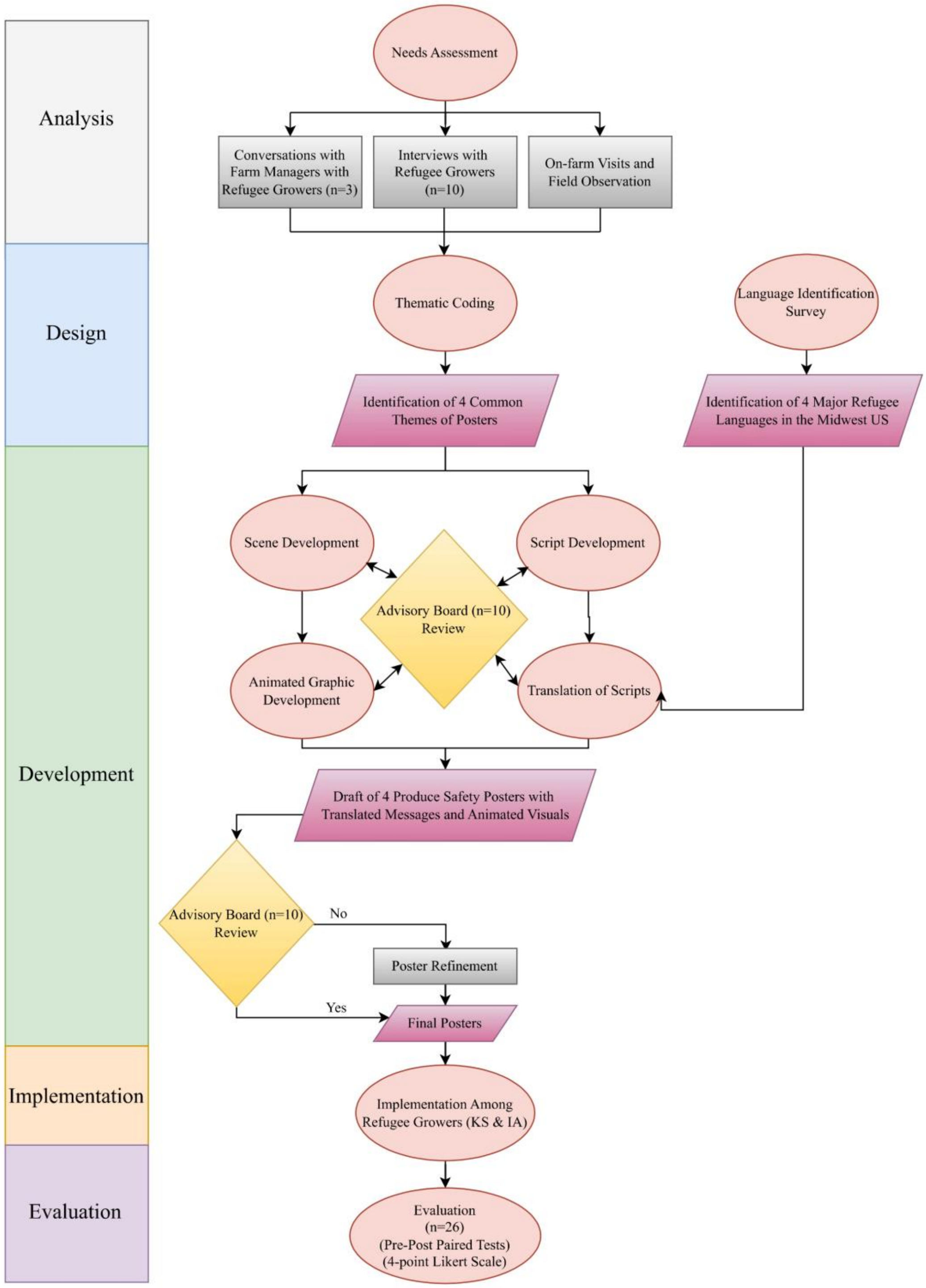

Figure 2.1. Methodological Framework Using Integrated ADDIE-Model for Poster Development

Phase-1 Needs Assessment

Food safety interventions focusing on the development of food safety-based educational resources or food handler training have emphasized the necessity of determining gaps in food workers' knowledge or identifying difficulties in the implementation of food safety practices, which is essential in creating an effective food safety intervention (Nabwiire et al., 2021; Nik Husain et al., 2016). Previously established gaps in food safety knowledge have been a significant hindrance for fresh produce growers. An inadequate basic knowledge related to food safety, such as correct handling of soil amendments, use of agricultural water, farmers' hygiene, and sanitation has resulted in many fresh produce growers being unable to exercise safe food practices on farms effectively (Chen et al., 2021; Doyle et al., 2023). Although educational resources have been developed to improve the knowledge of the growers, research consistently demonstrates that educational materials not based on the realities of learners have little effectiveness in modifying behavior (Soon & Baines, 2012). Because of these findings, this study focused on understanding the existing gaps in knowledge and practices of fresh produce growers to make the resources centered around the needs and relevancy of the growers.

Stakeholder Identification and Advisory Board Formation

A multidisciplinary advisory board made up of university extension personnel, non-governmental organization personnel, food safety educators, and refugee growers' representatives was formed. The advisory board helped gauge diverse viewpoints to render the cultural relevance, validity, and functional utility of educational interventions (Cueva et al., 2020; Newman et al., 2011). It also enables the linking of academic knowledge with community practice, thereby grounding interventions in genuine, practice-based knowledge (Dickson et al., 2020).

Non-governmental Organizations, including Catholic Charities of Northeast Kansas, Cultivate KC, and Lutheran Services of Iowa (LSI), provided key support for this project, enabling the implementation of culturally responsive engagement strategies. Intermediaries whom the audience trusts and confides in are vital to facilitate communication, enhance trust, and promote the participation of underrepresented communities, as shown in health education interventions (A. M. Anderson et al., 2024). With the engagement of stakeholders throughout, this project ensured that the resources aligned with actual farming conditions, linguistic requirements, and cultural practices, hence enhancing the prospect of effective implementation and practical use of produce safety posters on the farms.

Identification of Produce Safety Gaps

To identify and reconfirm the unique produce safety knowledge gaps, multiple approaches were employed, such as conversations with advisory board members, including farm managers supervising refugee growers across the Midwest states, interviews with refugee growers, and farm visits.

Farm managers, based on key observed practices of refugee growers, emphasized a need for a better understanding of food safety concepts, regulations, and good practices related to worker health and hygiene, use of Biological Soil Amendments of Animal Origins (BSAOOs) such as animal manure, blood meal, and feather meal on produce farms, and possibilities of contamination of fresh produce in different farming activities through various sources including post-harvest water and animal intrusions. Based on these key topics, a list of semi-structured interview questions was developed for the refugee growers to understand their knowledge levels.

Further insight into produce growers' knowledge was studied through the use of semi-structured interviews and focus groups (n=10) via trained interpreters who were fluent in growers' native languages. Through support from Cultivate KC, Catholic Charities of NE Kansas, and Lutheran Services in Iowa (LSI), 10 refugee growers were recruited for the needs assessment. Out of the estimated refugee grower population of 67 (actively working with support from these organizations and involved in growing and selling fresh produce), based on the multi-dimensional approach of identification of produce safety gaps, growers from different origins and language backgrounds were selected. The grower recruitment process was handled by the supporting organizations and their graduate program manager. Participants were selected for this process through the organizations to ensure that there was a good mix of people with different levels of farming experience, educational levels, training experience, and from different cultural backgrounds. Based on the recruited growers, in Iowa, two focus groups were conducted with Nepalese (n=3) and Kirundi (n=2) speaking growers in the presence of interpreters of the respective language. In Kansas, independent one-on-one interviews were conducted with Swahili (n=3) and Burmese (n=2) speaking growers with the assistance of the respective interpreters. The use of interpreters in qualitative research involving participants with diverse backgrounds, such as non-English-speaking refugee populations, is necessary as it adds validity and accuracy to the data collection process and prevents the misinterpretation of the intended response of participants as a result of language barriers (Squires, 2009). The interviews were drafted to highlight specific fresh produce safety issues, such as understanding of produce safety concepts, grower's knowledge and practices regarding hygiene on the farm and ensuring proper health conditions while working on the farms, understanding of different areas and avenues for contamination of fresh produce on farm, risk factors of biological contamination through people in the farm, use of agricultural water for pre- and post-harvest uses, and other factors, which are areas that have been noted previously as high-risk contamination sectors in other studies (Olaimat & Holley, 2012; Soon & Baines, 2012). Within each topic of discussion, probe questions were asked to get detailed insights and understanding of each participant on what they think about each aspect of fresh produce safety, both their understanding as well as practices (Appendix Table A.1). The participants were briefed about the purpose of the needs assessment, the use of the collected data, and confidentiality and voluntary participation, and completed a consent form developed through Institutional Review Board (IRB) approval. Each focus group discussion lasted for one hour for each group, while each one-on-one interview lasted for 30 minutes per participant. In addition to the discussion on fresh produce safety topics, demographic information was also collected to make an informed decision regarding what demographic group lacks or lags in terms of fresh produce knowledge and practices. The participants were provided a $50 gift card as compensation for their time and involvement in the needs assessment.

Repeated observational visits to the growers' working sites gave an understanding of growers' daily practices and available resources, the problems they faced, and what improvements can be made to best utilize their available resources and minimize the produce safety risks in their working conditions on the farm, offering essential contextual understanding that surveys could not always provide. Ethnographic approaches are widely regarded as valuable in agricultural and food safety studies since they enable researchers to observe behaviors, environmental characteristics, and informal practices directly, which participants might not disclose via self-report (Bernard, 2018).

Identification of Target Languages

Through the initial conversations with the supporting organizations, it was acknowledged that there is a large linguistic diversity among non-English-speaking refugee fresh produce growers. A language identification survey was carried out in partnership with these organizations to ensure that the educational materials developed are culturally and linguistically sensitive and appropriate for growers in this region. The primary objective of this survey was to identify the major languages spoken by the refugee growers and to tailor the development of the posters to the languages spoken by the majority of the growers. With multiple languages, identifying the most commonly spoken languages within the targeted population constitutes an integral component of effective educational outreach, as language is very crucial for practice adoption by both refugee and immigrant groups (J. G. Grzywacz et al., 2008; Nguyen & Delate, 2020). The survey identified that Swahili, Burmese, Kirundi, and Nepali were the most predominant languages spoken by refugee growers' communities.

The survey focused on developing and presenting critical educational information in the languages that have been shown to enhance comprehension, recall, and attitudinal and behavioral changes regarding food safety and farm education (Pérez et al., 2006). The use of appropriate language facilitates a more effective understanding of complex food safety concepts and regulations, fostering an environment of respect and cultural affirmation that is essential for building trust within immigrant communities (Arcury & Quandt, 2011; J. G. Grzywacz et al., 2008).

The implementation of the language identification process supports customizable educational materials for specific local contexts, rather than using generalized, translated English content that fails to account for essential cultural elements related to farming and food safety. This step, identifying preferred languages, helped to develop educational resources for multicultural settings.

Phase-2 Design of Themes

From the findings of the focus groups and interviews, the participants’ responses were recorded (with informed consent), transcribed into text, and qualitatively coded and analyzed to identify the areas of focus for poster development.

Grounded theory-related methods were employed in qualitative coding, ensuring that the analysis was grounded in the narratives of participants and not predetermined by pre-existing templates. Grounded theory is most appropriately suited for studies of underrepresented groups or immigrant communities, considering how it emphasizes theory construction from the lived experiences of participants and thereby offers an original articulation of their realities (Corbin, 2015). This involved a step-by-step procedure that comprised open coding, axial coding, and selective coding.

During open coding, the interview data were divided into their component parts (based on the topic of discussion or interview), assigned short identifiers or codes for each topic and response, and compared similarities and divergences. The next step was axial coding, where the coded data were reconstructed by establishing relationships between categories and subcategories (i.e., the answers or responses of each participant to different questions within various categories) and identifying interrelations among the different aspects of growers' practices and knowledge. The final step was selective coding, where core categories were developed into a consistent narrative to identify a common theme of fresh produce safety issues or gaps, which provided the framework for developing produce safety posters.

To develop these themes, a thematic analysis was implemented by classifying the interview information into 11 thematic categories and 39 response codes. Thematic coding in qualitative research enables the systematic identification of patterns, barriers, misconceptions, and cultural issues that affect behavior (Braun & Clarke, 2006). Coding the responses of the growers helped to collect and combine complex narratives into workable themes that could be used to directly inform the creation of educational material. This method also conforms to the principles of community-based participatory research by ensuring that the views and lived experiences of immigrant farmers inform the development of educational materials (Vaughn & Jacquez, 2017). The data coded from the interviews with the refugee growers formed the basis of the thematic development of the produce safety posters.

Phase-3 Development of Posters

Script Development

Each identified primary theme was subdivided into secondary themes, including concepts of produce safety practices for each topic, key fresh produce safety practices for each theme, the importance of adopting those practices, and the regulatory compliance needs (if present, as outlined in the FSMA Produce Safety Rule). The composition of each poster script was written with deliberate care to be in accordance with the FSMA Produce Safety Rule, while simultaneously filling the specific food safety knowledge gaps identified in the needs assessment process among growers (Produce Safety Alliance, 2019; United States Food and Drug Administration, 2015). By following the principles of Cognitive Load Theory, the scripts were intentionally limited to approximately 200 words to minimize the overloading of information and long text which affected fresh produce growers, particularly those with low literacy or no English proficiency (Sweller, 2011).

It has been observed that simple text with reduced complexity benefits the comprehension and information retention of individuals with reading difficulties (Perry et al., 2012; Zainurrahman et al., 2024). By limiting script length, the essential information was highlighted, and readability was improved for key food safety practices, thereby increasing the likelihood that growers would read and implement the recommended practices.

All of the scripts were carefully organized into logical sections to promote clarity and direction:

- **Title:** The title highlighted the general theme of each poster to give an overview of the topic addressed in each poster.
- **Fragment Title:** The fragment title provided an overall idea of a distinct sub-section or stand-alone concept, or practice to distinctly divide each theme into key components.
- **Main Message:** This explained simple and brief concepts or practices related to fresh produce safety within each key component, providing concise but critical information.
- **Sub Message:** It was used to provide a further explanation of suggested practices or visuals used on the posters to enhance the understanding of the main message, as well as visual components.

This scientific and tiered design of the script followed the principles of multimedia learning theory, focusing on the segmenting principle that suggests that the division of information into short sections enhances learning outcomes, particularly for English as a second language and adult learners (Mayer & Moreno, 2003).

A relevant fragment in each script was created first to address “why it matters”, an approach that has proven effective in improving learner motivation and personal commitment toward behavioral transformation (Sinley & Albrecht, 2015). The fragments that followed the first fragment were focused on regulations and recommendations based on produce safety practices, delivering tangible and behavior-specific direction, an approach that has been proven more effective in extension in agriculture and health education in low-resource settings (Kilonzo-Nthenge et al., 2018).

Scene Development for Visual Representation

In this phase, carefully detailed scene descriptions were written to assist with designing visuals that could depict the growers' farming conditions and practices, show food safety issues, and suggest produce safety practices with the provision of visual authenticity as well as cultural appropriateness to enhance message relevance and comprehension. This step provided a detailed description necessary for the development of visual components such as images or photos that will be culturally appropriate, visually detailed and engaging for growers to visualize the impact of their farm behaviors and to understand stepwise directions for the recommended food safety practices (Houts et al., 2006; Rajagopal, 2012; Rajagopal et al., 2019).

Each scene was designed to depict:

- Farm environments like small vegetable plots, shared wash station environments, and packing houses observed during farm visits.
- Activities that reflected proper food safety procedures on the farm, i.e., hand washing before touching fresh produce and after using restrooms, sanitizing equipment and tools, and application of fertilizers before planting produce crops.

For the characters, culturally appropriate representations of clothing, farming gear, and farm setups were descriptively detailed in each scene using the reference images to ensure that clothing styles, farm buildings, and farming methods were recognizable and respectful of growers' backgrounds. Such an approach allows for reducing cognitive dissonance and increasing perceived message relevance (Dworkin et al., 2015; Kreuter et al., 2003).

Culturally sensitive images are powerful cognitive aids, particularly for low-literacy and English as a Second Language (ESL) users who may rely more extensively on visual data for comprehension (Houts et al., 2006). Hence, accurate scene construction according to real-world relevance and cultural sensitivity was adopted to maximize the accessibility, authenticity, and effect of the fresh produce safety posters.

Educational materials in agricultural extension can become more relevant and effective if animated visuals that depict normal farm settings and growers' practices are used. This is because the target audiences can learn from animations that depict memorable working spaces of their familiar environments (Bello-Bravo et al., 2015; George & Joseph, 2023). Also, the animated scenes present farm activities reminiscent of real-world activities, which creates a bridge between theoretical knowledge and hands-on learning for the growers. In agricultural education resources, animation has proven beneficial as it allows farmers from various ethnic backgrounds who interact with different cultural groups to be depicted as characters (Bello-Bravo, Tamò, et al., 2018). Similar works among underserved communities show that learning engagement and retention improve when students recognize their own culture in instructional materials. The addition of culturally inclusive features in educational materials helps participants recognize themselves and fosters trustworthiness in the content, as it acknowledges real-life situations across various cultural groups (Gay, 2000). Therefore, an effective food safety education relies on well-designed animated visuals, accompanied by characters that serve a purpose beyond aesthetic benefits. It improves trust and credibility, which is essential for the success of any educational resources targeting underserved audiences like immigrant or refugee growers.

Layout Development

After the scripting and scene development for the fresh produce safety posters were completed, a multistep design process was used to lay out visual and text elements that were sensibly integrated within each poster. The approach was focused on evidence-based design and integrated feedback from a multidisciplinary advisory board.

The final scripts were integrated with the visuals based on cognitive load theory to facilitate understanding and reduce cognitive load (Mayer, 2014). Each layout was designed with a grid-based approach to keep the headings, images, and text blocks aligned and readable. This facilitated intuitive navigation in accordance with the principle of reading gravity, which highlights that the reader tends to move from the top left to the bottom right of a page (McTigue & Flowers, 2011).

The first designs were examined by the advisory board and professional graphic designers. Their comments helped to guide changes that strengthened the link between visual and written material, such as positioning related images and text near one another to support the meaning and provide a continuous flow of step-by-step instructions, minimizing visual clutter, and content overload, and maintaining uniform alignment and spacing, which have been previously identified as barriers to effective educational tools (Houts et al., 2006).

The advisory board also provided feedback to improve accessibility, effective design, and cultural relevance enhancement. The main suggestions for this improvement were to use white space and relevant graphics to help understand and organize material logically and replace technical words with familiar ones following plain language ideas. These suggestions were included along with the standardized font choices in updated designs to guarantee the materials were suitable for a wide audience.

Translation of Poster Messages

To make the posters accessible and clear to non-English-speaking fresh produce growers, all poster scripts were translated into four key languages: Swahili, Burmese, Kirundi, and Nepali, For any educational resource to be able to deliver effective communication to its audience, especially the ones with limited English proficiency or audiences who do not speak the primary language of a region, high-quality translation of messages is necessary (Pérez et al., 2006; Thomas A. Arcury & Sara A. Quandt, 2011). So, the translation process followed a collaborative and culturally sensitive approach. Rather than depending on automated methods of translation or methods that rely solely on back-translations, which may fail to capture the cultural nuance or idiomatic clarity of the messages (Squires, 2009), the model of community-informed translation and validation was used. The translations were performed by community members, who are native speakers of the relevant languages and had prior experience conducting interpreting sessions and handling translations of other written materials in the respective languages, showing experience in professional translation and direct ties to the respective communities.

After this first translation, an independent secondary translator, a native speaker who had no part in the original translation, carried out a wide-ranging review of each script. This was done in collaboration with personnel from Catholic Charities of NE Kansas and Lutheran Services of Iowa (LSI), s. The reviewers were fluent in both English and one of the four native languages. This validation of translation was focused on three major areas of concern: semantic accuracy, cultural appropriateness, and alignment with the intended educational tone and food safety guidance that the FSMA Produce Safety Rule sets forth. This independent review of the content was also a way to provide translation quality control through a form of peer evaluation, which has been previously identified as a way to improve the effectiveness of translated resources (Temple

& Young, 2004). This is a method shown to enhance the reliability and contextual integrity of translated educational materials in multilingual populations (Guillemin et al., 1993). Upon the completion of the review of translations, feedback and corrections suggested by the reviewing translator were discussed with the original translator to reach a consensus on revisions. These improvements involved modifications in word choice, simplification of technical terms, and preserving the intended behavioral guidance without overcomplicating the message —a common challenge in health and agricultural literacy for limited-literacy populations (Cueva et al., 2020; Vaughn & Jacquez, 2017).

Graphics Development

Once the script, translations, and scene descriptions were finalized, the next critical stage in developing the posters was creating culturally relevant animated graphics. In this developmental phase of the project, the primary objective was to visualize and depict the safe practices and regulatory guidance visuals in a way that was accessible and engaging to the target audience who did not speak English and had a limited literacy level (Fox, 2020; Li et al., 2015). The main goal was to display something simple yet effective so that a visual could be understood without a lot of words or extensive explanations. Thus, the visuals became the centerpiece in making an attitude and/or behavior change among the target audience.

Visuals were created not only to reflect the technical food safety recommendations of the FSMA PSR but also to show what happens when practices go wrong. For instance, to show what happens when sick farm workers work on the farm and handle produce or what happens when growing areas aren't protected from intrusion by animals. The graphics were designed based on evidence and principles known to enhance learning and retention. They were constructed using the

Cognitive Theory of Multimedia Learning (Mayer, 2014) and Dual Coding Theory (Paivio, 1990) as guides.

Each scene depicted specific fresh produce safety concepts, issues, or practices previously guided by the results from the needs assessment and the FSMA PSR. These focused on topics including worker sickness, visitor management, contamination of fresh produce by animal contaminants, and the application of biological fertilizers. The settings and characters in each scene were modeled after actual farm environments visited during farm visits in Kansas and Iowa, ensuring that the characters and environments resonated with the audience. The visuals used culturally resonant elements such as farm structures, tools, and the type of clothing depicted to increase the relatability and align with the produce safety messages. To ensure that graphics effectively reinforced educational content, each scene within a fragment followed the multimedia design principles of signaling, spatial contiguity, and coherence for the graphics to guide learner attention to where it needs to be (Mayer & Moreno, 2003), which is crucial when discussing potentially risky situations like foodborne illness resulting from contaminated fresh produce on farms. Instead of presenting static information, the visuals were designed to tell a visual story with a beginning, middle, and end, often showing a scenario where poor practice led to risk, followed by a correction that depicted the safe and recommended behavior. This narrative structure is particularly powerful in instructional design for diverse learners, as it allows them to learn from experience and examples of behaviors (Gay, 2000; George & Joseph, 2023).

After the initial graphics development, a comprehensive review process was carried out. This iterative review involved not just the core research team but also the project's multidisciplinary advisory board. The review also drew on feedback from community-based organizations such as Cultivate KC, Catholic Charities of Northeast Kansas, and Lutheran Services in Iowa. These last two groups provided invaluable help in ensuring that the visuals were appropriate to the cultural and educational backgrounds of the target population. Such participatory design practices help to ensure content validity and enhance user-centeredness in health and agricultural interventions (Cueva et al., 2020; Dickson et al., 2020).

The graphics were evaluated by reviewers based on several criteria: clarity, cultural accuracy, alignment with FSMA guidance, and appropriateness for low-literacy learners. Based on their evaluations, multiple adjustments were made to the graphics in several areas to reduce visual clutter, enhance character expressions and gestures to better depict actions, add details of cultural representation to the scenes and characters in the posters, and simplify complex processes into stepwise sequences so that visual representations do not imply more actions or decisions than are intended.

This iterative process meant that the visuals were not only scientifically precise but also rooted in the real-world, lived experiences of the growers as previous studies have shown that visuals reflecting the daily realities of learners dramatically enhance the probability of material acceptance, internalization, and long-term behavior change (Bello-Bravo et al., 2015; Rajagopal, 2012).

Phase-4 Implementation

Implementation

The implementation phase utilized Community-Based Participatory Research (CBPR) principles and leveraged partnerships formed with community-based organizations to recruit refugee growers for evaluating the posters, thereby gaining greater trust in participation (Israel et al., 2012; Wallerstein & Duran, 2010). The leading recruiters were program managers or farm managers from Catholic Charities of Northeast Kansas, Cultivate KC, and Lutheran Services of

Iowa (LSI), where internal networks were used to identify potential participants and directly contact the individuals in order to ask them to join the effort. The organizations employed various methods to communicate with the growers and make the case for their participation. This approach has been proven effective in tackling the observed challenges of accessing hard-to-reach refugee audiences who may harbor distrust toward formal research activities due to past experiences or cultural barriers (Betancourt et al., 2015; Ellis et al., 2007; Yakushko et al., 2008).

The recruitment plan employed purposive sampling (Patton, 2015) to ensure that the four target language groups identified in the needs assessment were represented in the evaluation. Organizational program managers at the participating sites helped to make initial contact with potential participants and ensured that screening was done confidentially, following established consent procedures. The inclusion criteria for participation were: (1) making a significant contribution to the production of fresh fruits and vegetables, (2) the primary language spoken is one of the four languages (Swahili, Burmese, Kirundi, or Nepali), and (3) being willing to participate in the evaluation. To offset potential barriers to participation that are common with refugee groups (e.g., time and money), each participant was provided $20. This level of compensation was determined in collaboration with community partners and was based on respect for participants' valuable time as well as sensitivity to the economic situations of refugee families. The method of compensation is in accordance with ethical guidelines in research among vulnerable populations, which aim at balancing the need for equitable compensation with the exclusion of undue inducement (Emanuel et al., 2004).

Interpreter Services and Cultural Mediation

With the acknowledgment of the critical role played by effective communication in multilingual research environments, qualified interpreters were recruited for each of the four target languages (Squires, 2009; Temple & Young, 2004). Interpreters were selected based on criteria of proficiency in their native language and experience in community interpretation.

The interpreters were briefed to make sure that the procedures for conducting the survey were uniformly followed. This practice is consistent with best practices in cross-cultural research, particularly with refugee populations, where interpreters can serve as cultural mediators and describe cultural nuances that allow for accurate translation of the meaning of interviews (Harkness et al., 2003).

Phase-5 Evaluation

Theoretical Framework and Conceptual Foundation

The evaluation plan was founded on the Theory of Planned Behavior (TPB), developed in 1991 by Ajzen, which is generally accepted as one of the most robust theoretical models for explaining and foreseeing changes in human behavior, especially in health and agricultural settings (Ajzen, 1991). This choice of TPB was driven by significant empirical evidence demonstrating that it could predict food safety practices among a wide range of groups, including refugees and immigrants (Rezaei et al., 2018; Roberts et al., 2020; Seaman & Eves, 2010).

The theory of planned behavior (TPB) predicts that intentions of an individual to engage in specific behaviors is a function of three primary components: (1) attitudes towards the behavior, or an individual's overall assessment of doing the behavior; (2) subjective norms, which convey the perceived social pressure regarding doing or not doing the behavior; and (3) perceived behavioral control, or an individual’s impression about being able to successfully execute the behavior (Ajzen, 2002; Roberts et al., 2020). This theoretical framework was particularly well-suited to the setting of this research study for several reasons.

First, TPB has been effective in predicting agricultural safety behaviors, and analytic results have demonstrated consistent relations between TPB constructs and behavioral outcomes across diverse farming populations (Lin & Roberts, 2020; Pirmoghni et al., 2024). Second, the framework's focus on subjective norms acknowledges the collective cultural preference of most refugee societies, in which social expectations and community support strongly shape personal decision-making plans (Fischer & Karl, 2022; Lin & Roberts, 2020). Third, the perceived behavioral control construct has strong applicability to refugee farmers, who may experience significant structural and resource limitations affecting their capacity to adopt recommended food safety practices (Soon & Baines, 2012).

Development and Validation of Survey Instruments

The evaluation surveys were developed by integrating the TPB measurement constructs with the specific content and setting of the educational resource, i.e. produce safety posters (Ajzen, 2006). For this, each of the four poster themes: Management of Sick Farm Workers, Management of Visitors on Produce Farms, How to Control Germs from Animals on the Farm, and Understanding Fertilizers and Their Risks were evaluated through a survey instrument with 16 items, four questions to measure each construct of the Theory of Planned Behavior (TPB).

In these evaluation tools, survey items were behavior-specific, appropriately scaled, and incorporated the conceptual domains of each theoretical construct. Attitude items assessed both instrumental attitudes (practical costs/benefits) and affective attitudes (emotional responses) to specifically produce safety practices. For instance, attitude questions included items like "Keeping records of fertilizers used on the farm is a good produce safety practice" (instrumental) and "Knowing whether farm visitors are healthy is important" (affective).

The subjective norm items asked about both injunctive norms (what individuals believe one should do) and descriptive norms (what individuals actually do) (Rivis & Sheeran, 2003). For example: "My farm supervisor expects me to let them know when I have any signs of sickness" (injunctive) and "My community values me using safe using proper fertilizer application intervals" (descriptive).

The perceived behavioral control (PBC) items measured both assessed self-efficacy (one's confidence in his or her ability to enact the behavior) and controllability (the degree to which performance is in his or her own hands), based on the two-component model (Ajzen, 2002). Examples were "Creating no-pick zones around produce areas with signs of animal-related germs is possible for me to do" (self-efficacy) and "When I am sick, it is possible for me to work in areas away from produce" (controllability).

The behavioral intention items assessed the respondents' motivation and determination to adopt certain produce safety procedures, in customary Theory of Planned Behavior (TPB) terminology, as translated into agricultural language (Ajzen, 2006). The motivation and determination of the respondents to adopt certain produce safety procedures were assessed through behavioral intention items. Sample items included: "I will not harvest produce that has signs of animal-related germs" and "I plan to follow a 120-day untreated fertilizer application interval for crops that have edible portions that touch the soil".

Expert Review and Content Validation of Evaluation Tools

The instruments were then validated through an expert review process with several steps. This process was designed to yield both theoretical accuracy and practical utility (Almanasreh et al., 2022; Zigbuo-Wenzler et al., 2020). The panel of experts included specialists who have experience with FSMA rules and produce safety standards.

The evaluation was focused on multiple dimensions including (1) alignment with Theory of Planned Behavior (TPB) constructs, (2) behavioral specificity and clarity, (3) cultural relevance to refugee groups, (4) technical correctness in relation to produce safety practices, and (5) linguistic complexity and readability.

An additional review was completed by a researcher with an extensive background in human subjects' research and cross-cultural methodology to assess ethical compliance and appropriateness for the target population. This review provided additional revisions aimed at minimizing participant burden, strengthening informed consent processes, and ensuring that questions would not inappropriately induce anxiety or distress in participants.

Gathering of Demographic Data and Contextual Variables

An additional survey was used to collect demographic data to find the necessary background for interpreting evaluation outcomes and to recognize potential moderating variables for poster effectiveness. The demographic questionnaire covered various dimensions of participant demographics recognized to affect processes of agricultural behavioral change (Botetzagias et al., 2015; Knowler & Bradshaw, 2007; Monroe-Lord, 2020).

Some of the sociodemographic characteristics used in the survey consisted of language, gender, age, years in the U.S., and training experiences. These variables were chosen according to research that demonstrated their relevance in the setting of agricultural technology adoption and food safety practice adoption among immigrant audiences (Arcury & Quandt, 2011; Gustavsen et al., 2021).

The agricultural experience measures included years of farming experience in the U.S., farm size, market outlets utilized, and previous experience in attending food safety training programs. These measures were important in valuing the participants' diverse agricultural experience and current production environments (Bello-Bravo et al., 2015).

Ethical Implications and Human Subjects Protection

To ensure ethical standards, Institutional Review Board (IRB) approval was received before dissemination of the survey. Proper ethical standards were maintained during the implementation process, as informed by elements of the Belmont Report and international research standards for engaging with vulnerable populations (Council for International Organizations of Medical Sciences, 2016; NRC, 1989). During the evaluation, comprehensive verbal informed consent through forms interpreted into their local languages by interpreters was received to ensure that participants were properly informed about the research.

This informed consent process addressed the major areas: the study's purpose and procedures, potential risks and benefits, confidentiality and anonymity measures, voluntary nature of participation and right of withdrawal, compensation policies, and contact information to seek questions or concerns (Barwise et al., 2019; Bhupathi & Ravi, 2017). Participants were communicated with through interpreters and given time to decide on participation on an informed basis without pressure or coercion.

Evaluation Design and Survey Administration Protocol

The evaluation used a pre-post method together with matched pairs analysis, an established method for examining the quick effect of education programs in the fields of agriculture and health promotion (Stein et al., 2010; Young et al., 2020). The design was selected because it was more practical, presented fewer ethical issues, and was meant to explore the poster assessment.

Participants’ data were gathered anonymously by assigning them codes that allowed comparison of their data before and after intervention (Audette et al., 2019; Lippe et al., 2019). A standard survey form was provided to participants to write their codes with non-identifiable details such as the first letter of their first name, the last letter of their last name, the first letter of their address, the last two digits of their birth year, and the last two digits of their phone number. This approach was effective in preserving privacy and matching data during sensitive research.

Pre-intervention surveys were conducted using a standardized protocol designed to be consistent across language groups and minimize interviewer effects on responses. The questions were orally read by interpreters using a standardized participant's native language, and the answers were documented on standardized survey forms.

The survey employed a four-point Likert scale response format (1 = strongly disagree, 2 = disagree, 3 = agree, 4 = strongly agree) to assess the levels of participant agreement with each statement (Appendix Tables B.1, B.2, B.3, B.4). A four-point scale was used rather than a five-point scale to follow methodological considerations in cross-cultural research. First, eliminating the neutral midpoint inhibited the satisficing tendencies and compelled participants to give directional answers (Westland, 2022). Second, four-point scales worked more effectively across cultures when neutral answers reflected cultural biases towards avoiding extreme labels instead of being neutral (Lee et al., 2023). Third, research working with individuals with low formal education showed that less complex response formats enhance understanding and response quality (D'Alonzo, 2011).

Poster Intervention Protocol

After finishing the pre-intervention survey, all participants were given the appropriate produce safety poster in their language using an identical protocol designed for equal delivery. The posters were viewed by the participants in a distraction-free, quiet, and well-lit environment where participants were comfortably seated and could look at the poster up close.

For every poster, a five-minute standardized intervention time was allowed for one-time viewing of the posters based on preliminary pilot testing with native language speakers. The time frame provided sufficient time for a thorough review of the poster but also maintained participants' interest and focus. During the intervention, participants were encouraged to examine all components of the poster, including graphic visualizations, text messages, and instructional steps.

For reliable implementation of the exposure protocol, the research team completed checklists listing the steps like displaying appropriate posters, monitoring the intervention session, and taking note of any difficulties or issues raised (Taniguchi et al., 2020).

Post-Intervention Measurement and Data Collection Procedures

After the intervention, the participants completed the post-intervention survey, where the same questions and administration procedures used during the pre-intervention measurement were used. A short duration between the pre-and post-surveys was intentionally selected in order to measure attitudes, perceptions, and intentions immediately following the intervention and minimize possible extraneous influences such as memory lapse, external factors, or intervening events (Davis et al., 2017; Medeiros et al., 2004).

Post-intervention administration of the survey was also done under the same standardized procedure as the pre-intervention assessment, with questions read by interpreters in the participants' native language. In this survey, the participants used the same personal identifier codes used in the pre-intervention survey to allow matched-pairs statistical analysis while maintaining anonymity. The data was collected through standardized paper-based questionnaires, which reduced the chances of recording errors and helped confirm the accuracy of the data.

Data Management and Quality Assurance Procedures

The questionnaires on paper were kept in secure filing cabinets at the research sites, and only authorized and trained staff could access them to protect the confidentiality of data (Krishnankutty et al., 2012). All survey results were double-checked, and any unmatched answers were corrected using the original questionnaires (Paulsen et al., 2012).

The participant identifier codes were treated by secure procedures that did not allow participant identity-linking of survey responses but enabled pre-post matching for statistical analysis. The association of identifier codes and participant contact details (used only for the payment of compensation) was stored in a separate, secure document in an independent manner.

Statistical Analysis

All statistical analyses were performed with the R statistical package (ver. 025.05.1-513) to test the effectiveness of visual produce safety posters on the behavioral constructs of growers based on the Theory of Planned Behavior (TPB) structure. The data obtained before and after the intervention were tested for constructs that met the normal distribution using paired t-tests, or Wilcoxon signed-rank tests for constructs that did not meet the normality assumptions. Both tests were conducted as two-tailed tests, with a significance level $\alpha = 0.05$ for determining statistical significance.

To determine the size of the changes observed, Cohen's d was calculated for each construct. In addition, 95% confidence intervals were calculated to determine the accuracy of the mean changes. In addition to the evaluation of pre- and post-intervention differences, correlation analysis between the four constructs (Attitude, Subjective Norm, Perceived Behavioral Control, and Intention) post-intervention was conducted. These were computed to explore the degree of internal consistency and coherence of behavioral drivers after intervention, based on the Theory of Planned Behavior.

Results

Themes of Posters

The primary themes identified through this coding were:

- Workers' Health and Sickness Symptoms
- Visitors' Management on Produce Farms
- Contamination on Produce Farms Through Animals
- Appropriate Application of Biological Soil Amendments (BSAs) on Produce Farms

These four themes were prioritized based on their frequency in interview responses, regulatory importance (as determined by the Food Safety Modernization Act (FSMA) Produce Safety Rule (PSR)), and the potential risk of contamination at produce farms where refugee fresh produce growers are working. One of the observed primary themes of "risks from post-harvest agricultural water use" was rejected for the development of educational posters, as the Water Rule from the FSMA Produce Safety Alliance (PSA) was undergoing review during the period of poster development.

Evaluation

Participant Demographics

A total of 26 growers participated in the evaluation of all four posters. The mean age of participants was 45.2 years (SD = 9.61), with a range from under 30 to over 60 years. Participants reported a mean farm size of 1.57 acres, although several larger farms (up to 10 acres) were noted (Table 2.2). On average, participants had 6.31 years of farming experience in the U.S.

The gender distribution was balanced, with 53.8% identifying as male and 46.2% as female. A high proportion of participants (69.23%) reported being currently enrolled in food safety training, while 15.38% had already graduated from some sort of food safety training program.

There was participation from growers from all four languages, with farmers speaking Swahili (30.78%), Kirundi (26.92%), Burmese (26.92%), and Nepali (15.38%) (Table 2.1).

The most common produce marketing channels indicated were farmers' markets (96.15%), followed by wholesale markets (30.77%) and restaurants (19.23%) (Table 2.1). Sales through churches, CSAs, and online platforms were also indicated.

Table 2.1. Summary of Participant Demographics, Training Background, Language Diversity, and Sales Channels

Variable	n	Percent or Mean (SD)
Age (years)	26	45.2 (9.61)
Farm Size (acres)	26	1.57 (2.5)
Years Growing in U.S.	26	6.31 (5.82)
Gender	Male	14
	Female	12
Food Safety Training	Graduated from a training program	4
	Enrolled in a training program	18
	No training	2
Language	Burmese	7
	Swahili	8
	Nepali	4

	Kirundi	7
Market Channels	Farmers Market	25
	Wholesale Markets	8
	Restaurants	5
	CSA	3
	Church	2
	Online	1

Values represent means with standard deviations (SD) for continuous variables and frequencies with percentages for categorical variables. These descriptive statistics characterize the demographic and agricultural background of the growers (n=26) participants included in the study. Some of the variables do not add up to 26 because participants chose not to answer the questions or provided more than one response.

Poster Evaluation

Poster 1: Management of Sick Farm Workers Poster

The intervention using the first poster (Appendix Figure C.1) titled "Management of Sick Farm Workers" achieved statistically significant improvements in all four constructs of the Theory of Planned Behavior. The evaluation showed the greatest improvement in the Perceived Behavioral Control (PBC) construct, where the mean score improved from a Likert scale rating of 3.10 to 3.48 ($p = 0.0001$, $d = 0.96$), suggesting that the use of the poster improved the confidence among participants in their ability to prevent food safety risks related to sick farm workers. Apart from this, there was also a significant improvement in worker attitude as it improved from 3.12 to 3.55 ($p = 0.001$, $d = 0.97$), indicating more positive views about the importance of proper communication of health conditions and taking preventive measures to prevent the contamination of fresh produce through sick farm workers. In addition, intention and subjective norms also increased with medium to small effect sizes (d = 0.58 and 0.46, respectively), showing the poster's potential to raise motivation and perceived social expectations despite a lower relative impact.

Table 2.2. Pre- and Post-Intervention Scores and Statistical Tests – Management of Sick Farm Workers Poster

Construct	**Pre-Mean (SD)**	**Post-Mean (SD)**	**Mean Change**	**95% CI (Lower, Upper)**	**Test**	***p*-value**	**Cohen's *d***	**Effect Size**
Attitude	3.12 (0.47)	3.55 (0.42)	0.43**	(0.22, 0.64)	Wilcoxon	0.001	0.97	Large
PBC	3.10 (0.35)	3.48 (0.44)	0.38***	(0.21, 0.55)	Paired t-test	0.0001	0.96	Large
SN	3.30 (0.45)	3.51 (0.46)	0.21*	(0.05, 0.55)	Wilcoxon	0.0239	0.46	Small
Intention	3.27 (0.50)	3.55 (0.45)	0.28**	(0.12, 0.44)	Wilcoxon	0.0018	0.58	Medium

For the construct with normally distributed data, a paired t-test was used, whereas for the construct where normality assumptions did not hold, Wilcoxon signed-rank tests were used. To assess the effect size, Cohen's d was computed. Mean differences and 95% confidence intervals were calculated to quantify and assess the precision of observed improvements across TPB constructs.

$p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

PBC = Perceived Behavioral Control; SN = Subjective Norm.

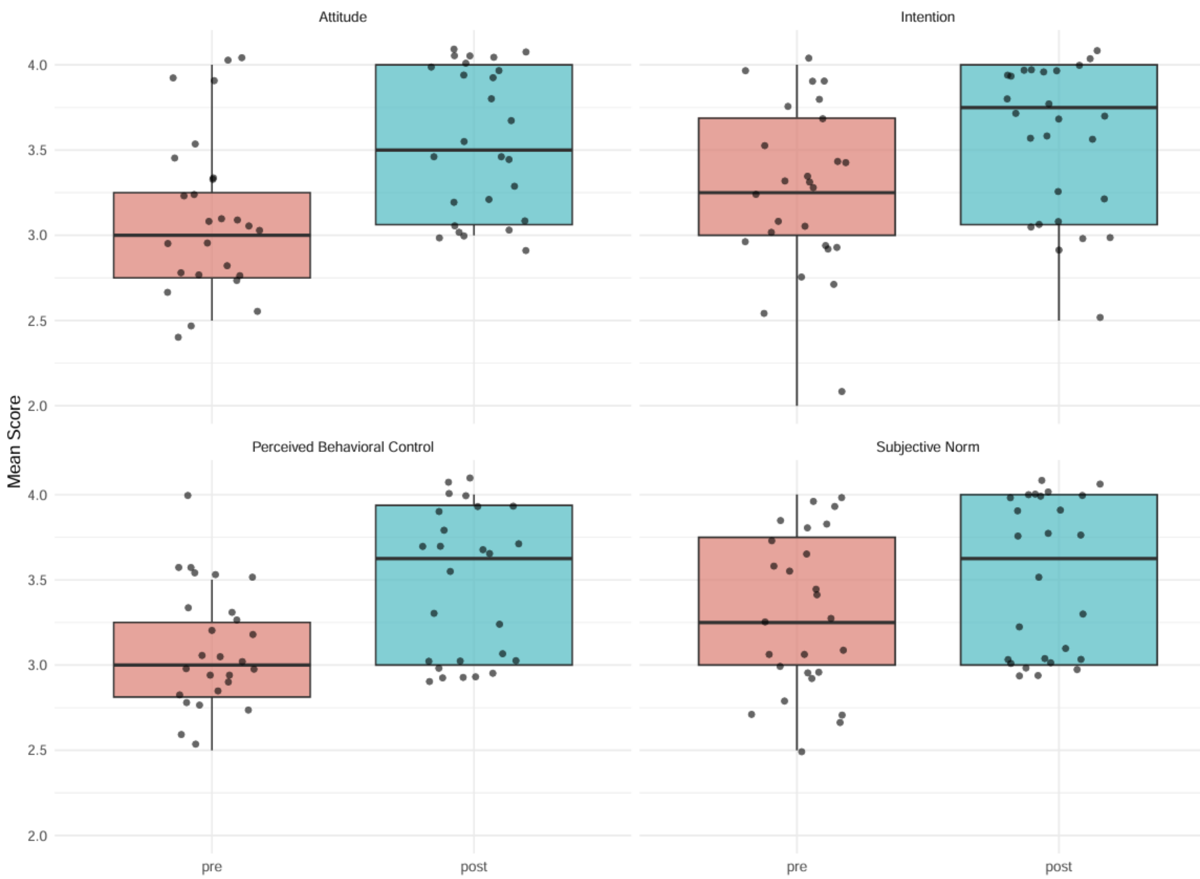

Figure 2.2. Pre vs. Post Boxplots for Theory of Planned Behavior (TPB) Constructs: Attitude, Subjective Norm (SN), Perceived Behavioral Control (PBC), and Intention Related to the Management of Sick Farm Workers Poster

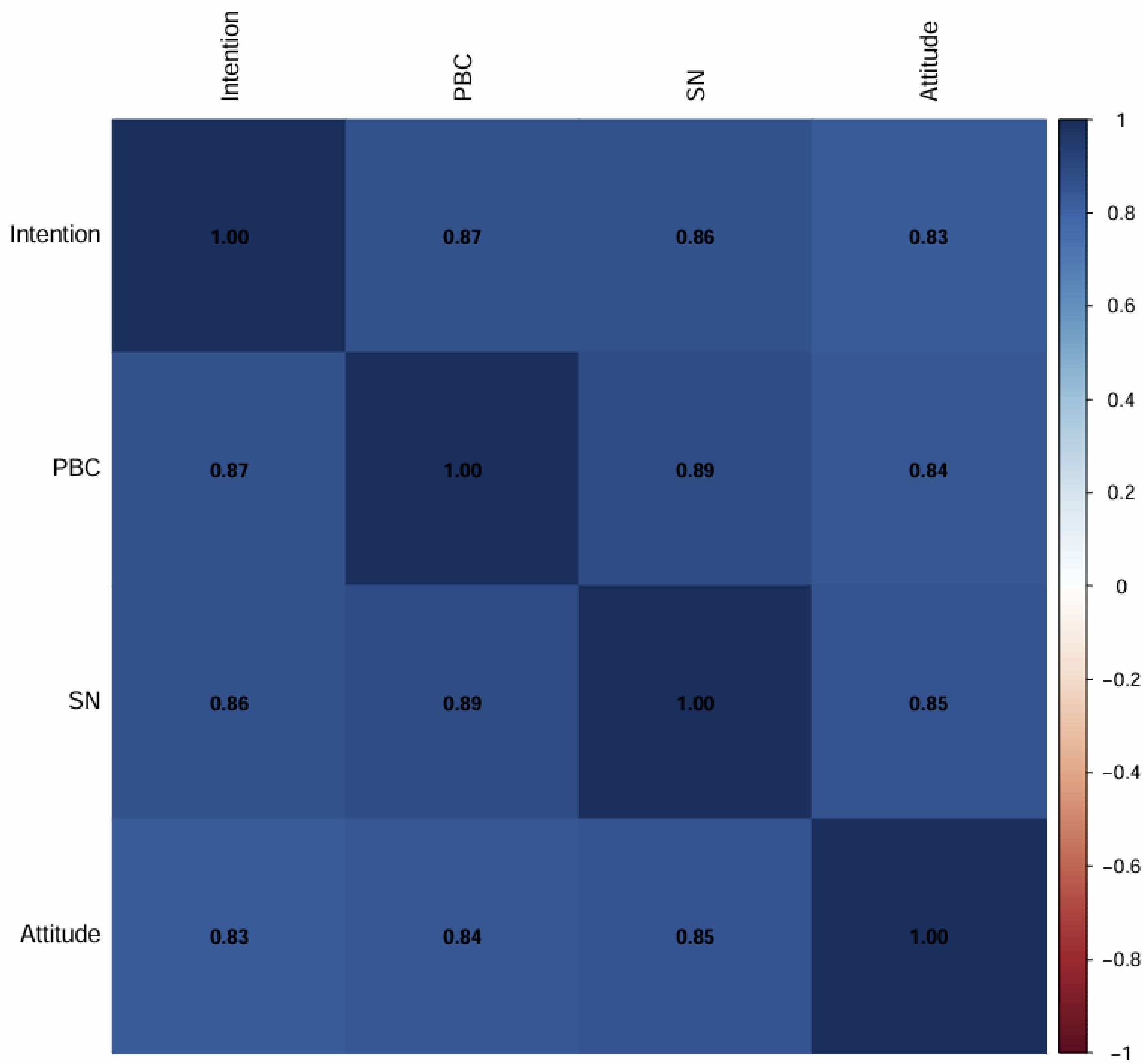

Figure 2.3. Correlation matrix illustrating the strength and direction of associations among post-intervention Theory of Planned Behavior construct scores for the Management of Sick Farm Workers Poster

After the intervention, a positive correlation among all the components of TPB was observed. It was found that intention is strongly associated with PBC, SN, and Attitude (r = 0.87, r = 0.86, and r = 0.83), which means that participants' motivation may depend greatly on their self-perception, social pressure, and beliefs. In addition, PBC and Attitude showed a high level of association (r = 0.84) and indicated that having confidence in food safety measures helps to improve attitude.

Poster 2: Management of Visitors on Produce Farms Poster

Through the evaluation of the second poster, “Management of Visitors on Produce Farms” (Appendix Figure C.2), a noticeable increase in all the TPB dimensions was observed. The biggest improvement was in PBC (from 3.12 to 3.55, p = 0.0004, d = 0.87) and Intention (from 3.03 to 3.46, p = 0.0004, d = 0.86), highlighting better confidence in managing visitors.

Table 2.3. Pre- and Post-Intervention Scores and Statistical Tests – Management of Visitors on Produce Farms Poster

Construct	**Pre-Mean (SD)**	**Post-Mean (SD)**	**Mean Change**	**95% CI (Lower, Upper)**	**Test Used**	***p*-value**	**Cohen's *d***	**Effect Size**
Attitude	3.49 (0.43)	3.64 (0.45)	0.15*	(0.03, 0.27)	Wilcoxon	0.02	0.35	Small
PBC	3.12 (0.53)	3.55 (0.46)	0.43***	(0.26, 0.6)	Wilcoxon	0.0004	0.87	Large
SN	3.17 (0.49)	3.51 (0.43)	0.34***	(0.14, 0.54)	Wilcoxon	0.0006	0.73	Medium
Intention	3.03 (0.55)	3.46 (0.44)	0.43***	(0.21, 0.65)	Wilcoxon	0.0004	0.86	Large

For all constructs, normality assumptions did not hold, so Wilcoxon signed-rank tests were used. To assess the effect size, Cohen's d was computed. Mean differences and 95% confidence intervals were calculated to quantify and assess the precision of observed improvements across TPB constructs.

$p < 0.05$ (*), $p < 0.001$ (***).

PBC = Perceived Behavioral Control; SN = Subjective Norm.

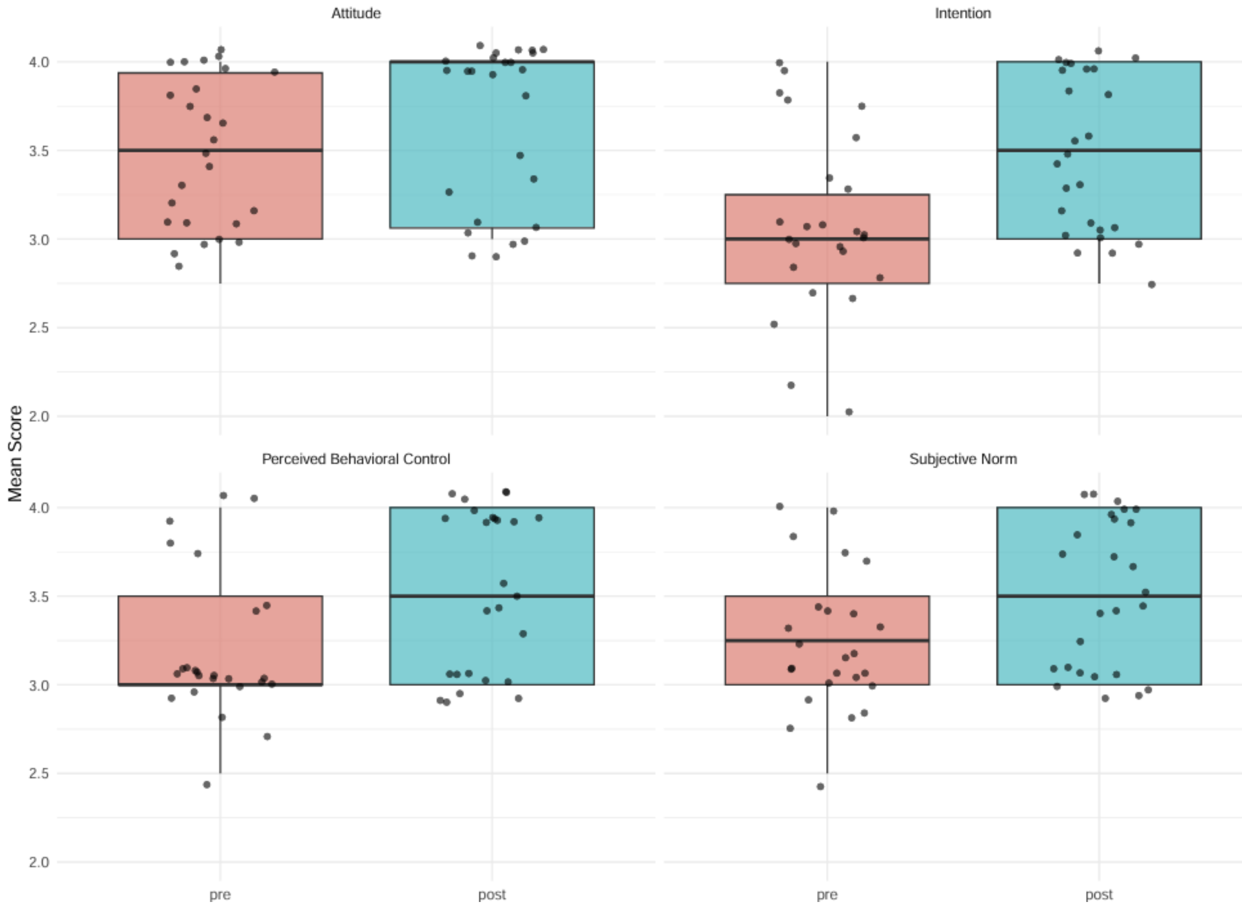

Figure 2.4. Pre vs. Post Boxplots for Theory of Planned Behavior (TPB) Constructs: Attitude, Subjective Norm (SN), Perceived Behavioral Control (PBC), and Intention Related to the Management of Visitors on Produce Farms Poster

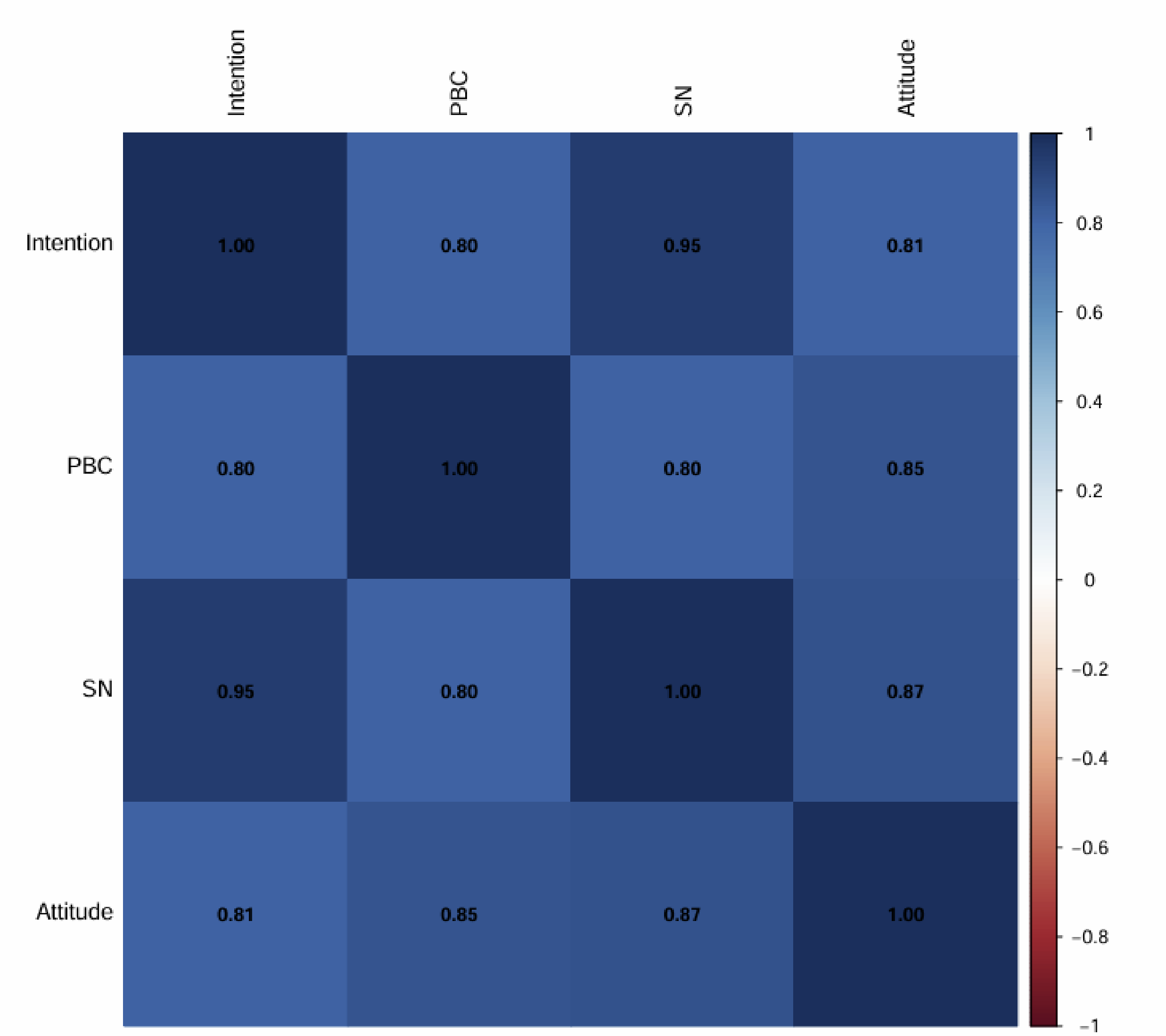

Figure 2.5. Correlation matrix illustrating the strength and direction of associations among post-intervention Theory of Planned Behavior construct scores for the Management of Visitors on Produce Farms Poster

According to the correlation analysis, the TPB elements had strong similar relationships on the "Management of Visitors on Produce Farms" poster. There was a strong relationship, with a correlation of 0.87, between Attitude and Subjective Norms, which can mean that those who saw visitor control as positive also felt strong pressure from others to implement it. Also, self-efficacy, personal opinion, and perceived norms had huge influences on PBC, as their correlations were both very high (r = 0.85 and 0.80, respectively). From this, it can be said that the poster might do well in motivating people to act, as it was linked to PBC and Attitude at a similar high degree (r = 0.80 and r = 0.81, respectively).

Poster 3: How to Control Germs from Animals on the Farm

After intervention with the poster, "How to Control Germs from Animals on the Farm" poster (Appendix Figure C.3) to the growers, it was observed that every construct improved significantly. The highest increase was in PBC, which improved from 3.14 to 3.62 (p = 0.0002, d = 1.07), which reflected a major improvement and increased confidence in dealing with animal contamination risks. Also, intention and attitude improved significantly (d = 0.96 and 1.08, respectively), whereas SN improved with a medium effect (d = 0.67). This can mean that a well-rounded impact was developed across all TPB dimensions with the poster 3 intervention among refugee growers, with its particular strength in altering internal motivation and efficacy beliefs.

Table 2.4. Pre- and Post-Intervention Scores and Statistical Tests – How to Control Germs from Animals on the Farm Poster

Construct	Pre-Mean (SD)	Post Mean (SD)	Mean Change	95% CI (Lower, Upper)	Test Used	p-value	Cohen's d	Effect Size
Attitude	3.27 (0.32)	3.65 (0.39)	0.38***	(0.21, 0.55)	Paired t-test	0.0001	1.08	Large
PBC	3.14 (0.47)	3.62 (0.40)	0.47***	(0.31, 0.63)	Wilcoxon	0.0002	1.07	Large
SN	3.24 (0.49)	3.55 (0.42)	0.31**	(0.14, 0.63)	Wilcoxon	0.0051	0.67	Medium
Intention	3.07 (0.59)	3.58 (0.45)	0.51***	(0.31, 0.71)	Wilcoxon	0.0005	0.96	Large

For the construct with normally distributed data, a paired t-test was used, whereas for the construct where normality assumptions did not hold, Wilcoxon signed-rank tests were used. To assess the effect size, Cohen's d was computed. Mean differences and 95% confidence intervals were calculated to quantify and assess the precision of observed improvements across TPB constructs.

$p < 0.01$ (**), $p < 0.001$ (***).

PBC = Perceived Behavioral Control; SN = Subjective Norm.

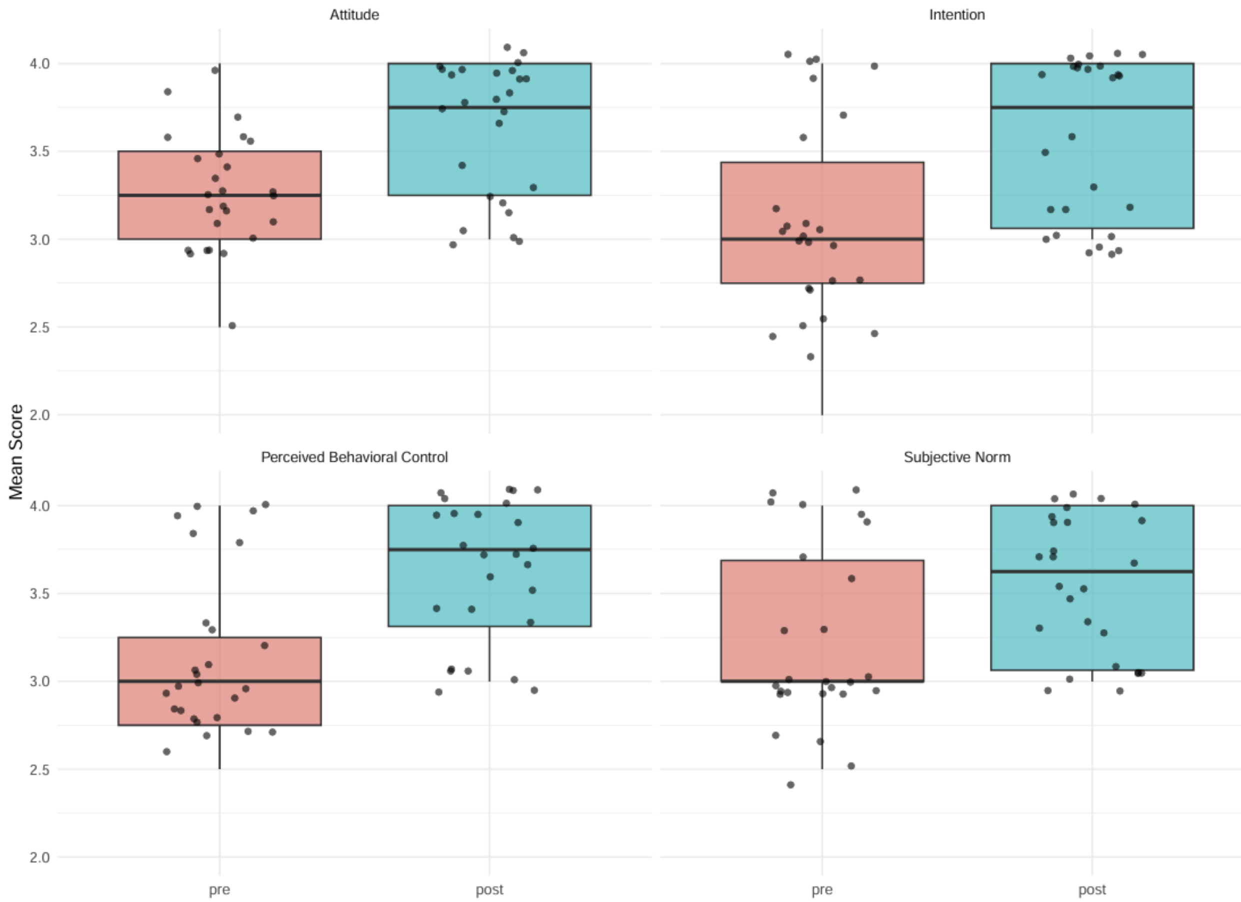

Figure 2.6. Pre vs. Post Boxplots for Theory of Planned Behavior (TPB) Constructs: Attitude, Subjective Norm (SN), Perceived Behavioral Control (PBC), and Intention Related to the How to Control Germs from Animals on the Farm Poster

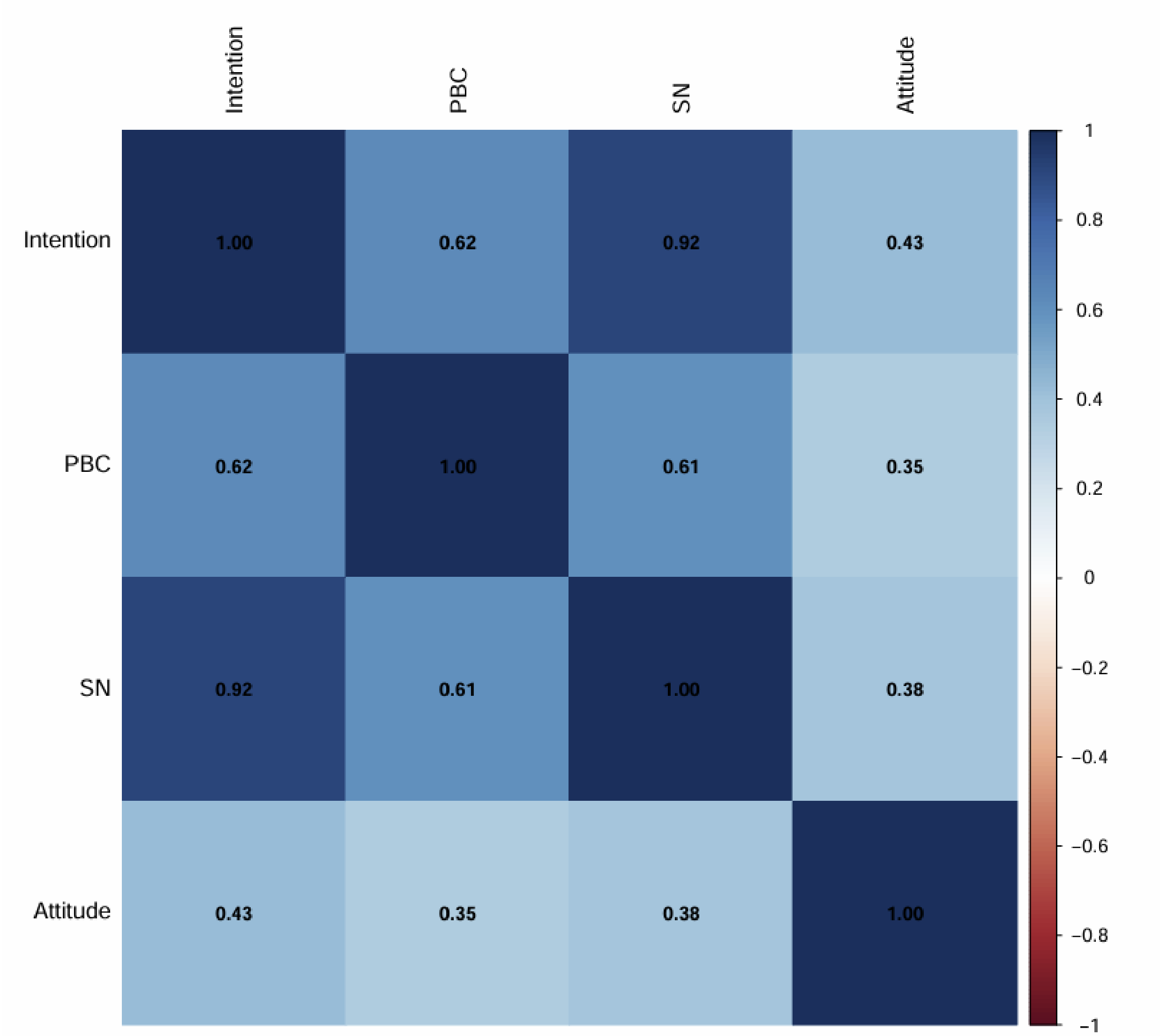

Figure 2.7. Correlation matrix illustrating the strength and direction of associations among post-intervention Theory of Planned Behavior construct scores for the How to Control Germs from Animals on the Farm Poster

In this case, when the "How to Control Germs from Animals on the Farm" poster was implemented, moderate to weak positive relationships among the TPB variables were seen. While the poster may have helped increase motivation and control, it did not have as big an effect on either attitude or social norms. The correlation between attitude and PBC (0.35) or SN (0.38) appeared relatively weak. This can mean that the message was interpreted more cognitively than effectively, enhancing a sense of ability without changing the perception of social expectations or value judgments. One of the causes for this can be that this poster mainly focused on food safety messages with the use of various potentially expensive and more difficult to implement resources such as fences, noise devices, scarecrows, and complex steps for limiting the contamination of fresh produce.

Poster 4: Understanding Fertilizers and Their Risks

All four TPB constructs improved considerably as a result of using the "Understanding Fertilizers and Their Risks" poster (Appendix Figure C.4). In the evaluation, intention and PBC showed the largest effect sizes (1.21 and 1.20), where intention went from 3.00 to 3.48 and PBC from 3.01 to 3.47. Positive effects were seen in attitude and SN, as both improved with very large effect sizes (d = 0.93 and 0.90).

Table 2.5. Pre- and Post-Intervention Scores and Statistical Tests – Understanding Fertilizers and Their Risks Poster

Construct	**Pre-Mean (SD)**	**Post-Mean (SD)**	**Mean Change**	**95% CI (Lower, Upper)**	**Test Used**	***p*-value**	**Cohen's *d***	**Effect Size**
Attitude	3.17 (0.38)	3.56 (0.44)	0.38**	(0.20, 0.56)	Wilcoxon	0.0012	0.93	Large
PBC	3.01 (0.31)	3.47 (0.44)	0.46***	(0.29, 0.63)	Wilcoxon	0.0004	1.20	Large
SN	3.12 (0.34)	3.49 (0.45)	0.37**	(0.20, 0.54)	Wilcoxon	0.0011	0.90	Large
Intention	3.00 (0.35)	3.48 (0.44)	0.48***	(0.31, 0.65)	Wilcoxon	0.0003	1.21	Large

For all constructs, normality assumptions did not hold, so Wilcoxon signed-rank tests were used. To assess the effect size, Cohen's d was computed. Mean differences and 95% confidence intervals were calculated to quantify and assess the precision of observed improvements across TPB constructs.

$p < 0.01$ (**), $p < 0.001$ (***).

PBC = Perceived Behavioral Control; SN = Subjective Norm.

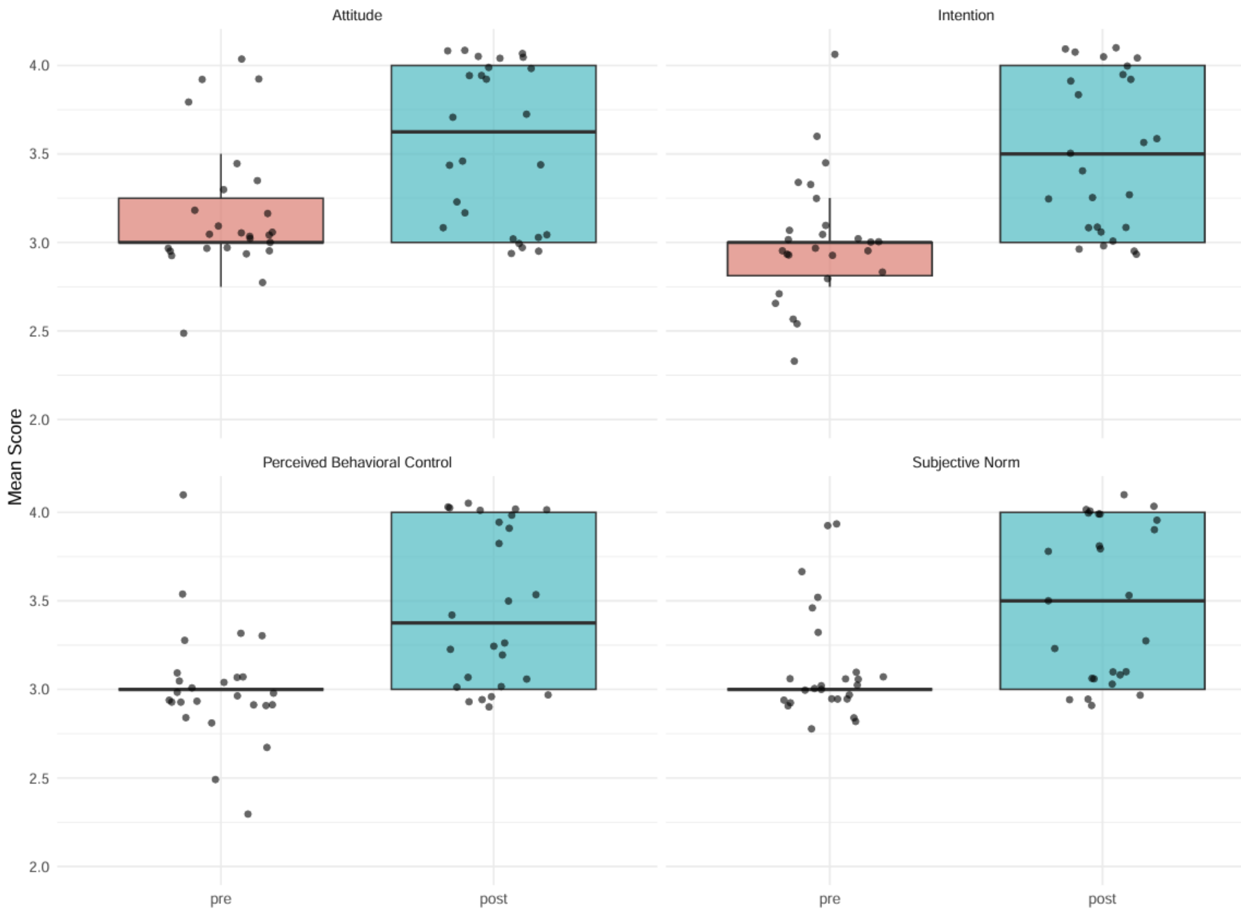

Figure 2.8. Pre vs. Post Boxplots for Theory of Planned Behavior (TPB) Constructs: Attitude, Subjective Norm (SN), Perceived Behavioral Control (PBC), and Intention Related to the Understanding Fertilizers and Their Risks Poster

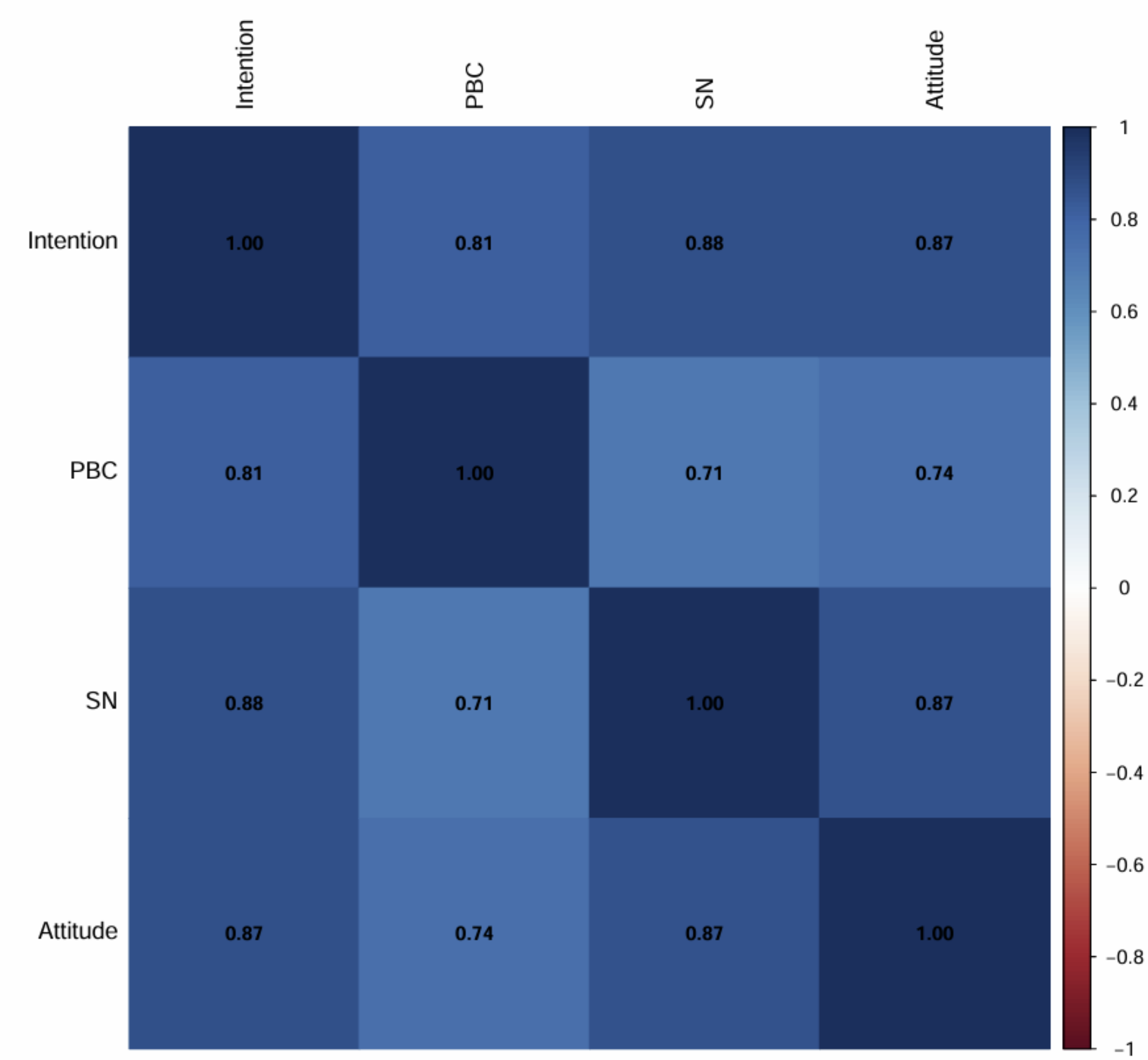

Figure 2.9. Correlation matrix illustrating the strength and direction of associations among post-intervention Theory of Planned Behavior construct scores for the Understanding Fertilizers and their Risks Poster

The poster on "Understanding Fertilizers and Their Risks" showed a clear, consistent correlation among different constructs of TPB as a result of Poster 4. The changes seen in attitude and subjective norms were similar (r = 0.87), meaning that those who had a positive view of fertilizer safety also reported experiencing peer pressure to engage in such safety measures. The self-efficacy measured by intention had a strong link to PBC (r = 0.81), suggesting that it can play an important role in influencing motivation. There were strong links between PBC and both SN (r

= 0.71) and Attitude ($r = 0.74$), reflecting that all three are closely connected in influencing people's willingness to act. From these observations, it can be said that the poster effectively involved both internal and external motivational factors to educate people about fertilizers and the risks they carry.

Overall, the four posters were successful in improving growers' attitudes and motivation regarding the practices that they can follow for the safety of their produce. Out of all the posters, "Management of Sick Farm Workers" and "How to Control Germs from Animals on the Farm", were the most effective in improving attitude and intention. The "Management of Visitors on Produce Farms" poster showed the highest PBC improvement, and the "How to Control Germs from Animals on the Farm" poster improved all constructs of TPB equally. It was observed that the posters acted upon and invoked strong relationships between the various constructs of behavior change, suggesting that people noticed all the messages and showed an improved behavioral intention accordingly. These results suggest that visual educational materials tailored to different cultures can help shift key factors influencing the behavior of growers toward fresh produce safety.

Discussion

The overall goal of the research was to improve the fresh produce safety practices among non-English speaking refugee and immigrant growers in the Midwest by developing and evaluating needs-driven culturally and linguistically relevant visual learning materials. The findings of the study reveal that minimal text, linguistically tailored, and visually driven posters in fresh produce safety positively impacted the key factors behind produce-safety behavioral intention among non-English-speaking refugee produce growers. The intervention (4 posters) showed that attitude, subjective norms, perceived behavioral control, and intention, the main constructs of the Theory of Planned Behavior, improved among growers after viewing the posters.

Besides better individual construct scores, stronger correlations between constructs after the intervention signify better behavioral integration, meaning not only did participants rate better scores on individual measures, but they also established more consistent internal behavioral structures, where confidence, social norms, and positive attitudes additionally support their intention to act safely. As most of these gains were consistent and practically impactful with large to medium effect sizes (Cohen's d), it signifies that when such an audience views a well-designed visual poster, it can change growers' likelihood to adopt a safer practice on the farm.

According to TPB, stronger attitudes, supportive norms, and higher PBC are expected to increase behavioral intention and, in the end, improve performance (Ajzen, 1991; Nickell & Hinsz, 2023). Similar to this belief, the four produce safety posters in this study, upon evaluation, found that the constructs that improved the most were PBC and intention. It was also found that these two constructs were the ones that were most strongly correlated after the intervention, showing that those who felt capable of acting were also more willing to act. The strong link between PBC and intention in this study is similar to results seen in a bilingual virtual food-safety course, where a TPB curriculum for low-income caregivers led to the biggest improvements in PBC and intention (Archila-Godínez et al., 2022).

The improvements in attitudes, intentions, and perceived behavior control observed here among growers were greater than those observed in past food safety education studies based on paper-based visual materials. Compared to the findings of a pilot study for visual posters for farmers' market vendors, despite being well-received (Jan et al., 2021), it did not lead to any changes in attitude, likely because it was not tailored to the culture or language of the audience. However, in our study, the posters used the English language very occasionally (only where it was necessary to be familiar with words such as "seed," "time," and "germs"). Images were used that provided step-by-step illustrations to establish context and suggest proper practices for each food safety behavior and were published using four different languages. Since the four posters developed in this study have a fragmented pattern, making the message clearer (establishing contexts, showing risks, and providing recommendations), this could have helped simplify growers' understanding of the food safety risks and recommended practices. Comic-style materials, with their use of pictures and short stories, have always performed better than simple brochures when training food handlers (Dworkin et al., 2013; Manes et al., 2014). The use of animated visuals and characters in this study can be attributed to the significant improvements across various constructs of TPB, helping growers to understand the critical concepts, importance, and ways of adopting produce safety practices, ultimately improving their confidence to implement and intention of adoption. The significant improvements seen in PBC suggest that using actionable visuals and scenarios that fit each grower's needs is more useful for boosting self-efficacy than using general messages.

The highest improvement in PBC was observed through the posters titled "Management of Sick Farm Workers" and "Management of Visitors on Produce Farms Poster", showing that visual cues and reminders help in building self-efficacy to maintain proper health and hygiene (Dunlop et al., 2024; Elia et al., 2022), both for growers themselves and their coworkers and visitors. In the poster "How to Control Germs from Animals on the Farm", the correlation between different constructs was the lowest. A possible reason is a cognitive load: the poster had the most risk scenarios showing the impact of their practices on farms on the health of their consumers, which could have led people to have doubts about their own ability and the availability of the necessary resources (Soon & Baines, 2012; Sweller, 2011). It is better for beliefs to be connected to a person’s ability rather than dependence on resources for adoption, as this makes them more lasting and reliable in predicting future actions.

Similar studies have identified that visuals should reflect the audience’s daily lives to help overcome issues with literacy, language, and trust (Bello-Bravo, Zakari, et al., 2018; Devkota et al., 2020; Nabwiire et al., 2022). Therefore, the use of several languages, the use of visuals showing available farm resources, the use of small plots to depict small acreage farming and focusing on characters who look similar and wear typical attire of the refugee communities may have led to the positive results. The results are consistent with efforts in the U.S. Virgin Islands, where changing the imagery to suit local methods led to a better self-reported practice six months after the intervention (Nabwiire et al., 2022). However, poster interventions have not always been successful outside the area of food safety. A research study discovered that the use of eye-catching graphics did not lead to lasting improvements in handwashing (Lawson & Vaganay-Miller, 2019). Alternatively, the 4 posters in this study addressed several factors at the same time, suggesting that (i) focusing on a motivated group (ii) understanding the needs of the target audience, and (iii) including visuals that resonate with the audience can work better than a more generalized public educational campaign, an approach which can be very effective for developing food safety educational resources in the future. The main objective of this project was to develop educational posters for non-English-speaking refugee and immigrant growers, specifically those involved in small-scale or community-based farming. These materials, however, have more extended use beyond this particular audience. Besides assisting growers, these posters are also useful tools for extension agents, food safety trainers, community educators, and nongovernmental organizations working with diverse agricultural audiences. They can be used in produce safety training workshops, on-farm workshops, farmer field schools, and community outreach and education programs, particularly for growers from limited educational backgrounds and speaking these native languages. They can function as independent reminders posted at key locations on farms and as teaching aids during group training. This adaptability greatly increases their potential to be used to aid comprehension and adoption of food safety procedures by a large cross-section of audiences beyond the target audience.

Limitations of the Study

There were limitations in this study, including the small size of the sample, lack of comparison with a control group, and the use of post-tests right after the intervention. The improvements made in the constructs were used to predict behavior, but actual activities on the farm were not measured. To verify the long-term results, future studies should also focus on conducting additional checks after a delay and rely on measurable markers (like swabs for microbes and checklists for observing the behavior of growers on the farms). In addition to this, examining which way to deliver posters, either on the farm (through incorporation with training courses or informal use within the farm) or digitally, would help identify the most effective methods of education for various communities of growers.

Conclusion

The implementation of the ADDIE model, along with design-based research, with the cooperation and support of members of community organizations, growers' representatives, and food safety experts for the development of visual-based educational resources proved effective in addressing produce safety needs of refugee growers in the Midwest. The four posters, each with a different overarching theme, were designed for produce growers speaking different languages. The integration of clear and easy-to-understand visuals helped in significant changes in important factors of the Theory of Planned Behavior. The strong effect sizes for perceived behavioral control (d ≈ 0.9–1.1) and behavioral intention (d ≈ 0.9–1.2) demonstrate that short, visually driven educational materials can be more effective than traditional text-based training for people with language, literacy, or cultural barriers. Its ability to be used in multiple points, like packing sheds, storage areas, and other shared-use areas, without requiring special devices or instructors, as well as integration into training programs, allows for repeated and affordable ways of enhancing the training of non-English-speaking produce growers. In the future, scaling the model to cover different produce, languages, and ways of delivering information can help close persistent food safety knowledge and practice gaps, which in turn reduces risks of microbial contamination in the food produced by immigrant and refugee produce growers.

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Chapter 3 - Use of Novel UV-C Tunnel to Reduce *E. coli* Microbial Load on Carrots (*Daucus carota*)

Abstract

Outbreaks of foodborne illness associated with fresh produce, especially root crops like carrots, represent an ongoing pressing need to develop effective and sustainable methods of decontamination. This study explores a novel decontamination tunnel system to reduce *Escherichia coli* on whole carrots. The tunnel used four modules of Ultraviolet-C (UV-C) light and sanitizer spraying nozzles. The evaluations were conducted for the individual intervention as well as combinations of UV-C (254nm) and Peracetic Acid (PAA) (80 ppm). In a randomized controlled trial, four treatment groups were selected: control, treatment with UV-C only, treatment with 80 ppm PAA only, and treatment with combined UV-C and PAA. The test was conducted in three independent trials, with nine replicates per group (n=9 total). The reductions in microbial loads were expressed as Log CFU/g values. Notably, the UV-C combined with PAA treatment produced the greatest mean reduction of 2.83 ± 0.10 Log CFU/g, significantly higher than either that treated with PAA alone (2.38 ± 0.06 Log CFU/g) or UV-C alone (1.49 ± 0.16 Log CFU/g) at a p-value < 0.0001. The combination of PAA and UV-C light exhibited a complementary effect, with an effective combination that overcomes the limitations caused by the sole use of one or the other treatment individually. This approach has a direct influence on root vegetable surfaces like carrots, which have a rough surface with minute crevices and are difficult to decontaminate through a single treatment. This new tunnel-based technology combining UV and sanitizer applications has great potential as an additional second-line strategy to traditional sanitization techniques. Its applications, in addition to enhanced microbial safety of fresh produce and vegetables, also help to decrease the application of chemicals and provide an eco-friendly and health-conscious approach to ensuring the microbiological safety of fresh produce.

Key Words: UV-C light, Peracetic acid (PAA), *Escherichia coli,* Carrot decontamination, Fresh produce safety.

Introduction

The whole world remains at risk from various foodborne illnesses that result in a large socio-economic and public health impact. The U.S. is also heavily affected by this critical issue, as the US Centers for Disease Control and Prevention (CDC) reports that foodborne diseases affect 48 million Americans each year, while leading to the hospitalization of 128,000 individuals and causing approximately 3,000 deaths annually (CDC, 2018). The recent years present an alarming trend where foodborne outbreaks involving fresh produce have occurred more frequently, and the pathogens of public health concerns, such as *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes*, have emerged as primary pathogens responsible for the outbreaks (CDC, 2023). With these findings, it has been widely acknowledged that raw and minimally processed fruits and vegetables that do not have terminal kill steps are being consumed more in recent years and require more effective decontamination solutions with their increasing popularity and their contribution towards foodborne illnesses (Bhilwadikar et al., 2019; CDC, 2018; Melo & Quintas, 2023).

Recent Outbreaks Associated with Root Crops (Carrots)

Carrots are one of the most popular vegetables in the United States, with a mean per capita consumption of about 9.5 pounds per year (Davis et al., 2022). Although carrots are often used in cooked meals, including soups, stews, roasts, and pureed infant foods, raw eating is especially common, especially in processed forms like baby-cut carrots, shredded carrots, and carrot sticks. The popularity of these fresh-cut options is because of their convenience and can be found in ready-to-eat salads, lunchboxes, and snack packs. The emergence of baby-cut carrots in the late 1980s has radically changed the trends of carrot consumption; initially created to minimize waste of oversized carrots, the uniformly shaped and peeled carrots have become the primary products in the U.S. fresh carrot market (Pogue, 2022).

The commercial processing of carrots involves processing carrots in numerous ways to meet various market requirements. The most popular types are whole unpeeled carrots, peeled whole carrots, baby-cut carrots, sliced coins, carrot sticks, and shredded carrots. Also, carrots are canned, frozen, or dehydrated to have a longer shelf life and convenience. The shelf life of fresh-cut carrots is usually shorter (approximately 21 days) compared with unprocessed whole carrots (up to 180 days) when stored under appropriate cold storage conditions (Kader, 2002; Condurso et al., 2020). Through these processing steps, carrots are subjected to various handling and washing procedures, which pose a risk of microbial contamination, particularly in minimally processed forms of carrots that are eaten raw.

The extensive use of raw carrots, especially in baby-cut carrots, shredded carrots, and carrot sticks form, is associated with particular concerns regarding microbial food safety (Piscopo et al., 2019). The raw and minimally processed carrots are not subject to a kill step as compared to cooked products, which are subject to thermal processing and, therefore, rely more on pre-consumption sanitation. Because these foods are frequently consumed without additional washing or cooking, any contamination that persists after postharvest handling or processing can be directly consumed by the consumer.

For many years, leafy greens and sprouts that are generally eaten raw have been known as the major fresh produce categories linked with foodborne outbreaks and recalls. However, root crops, especially carrots, have recently been identified as carriers of foodborne pathogens (Dharmarha et al., 2019; Kwon et al., 2025; S. Park et al., 2023). There is an increased risk of contamination for root crops such as carrots, as their edible parts grow underground in direct contact with the soil, allowing pathogenic microorganisms to attach to the food surfaces (Machado-Moreira et al., 2019). The uneven surface characteristics and hydrophobic nature of carrots, resulting from low wettability, can help the microorganisms attach and form biofilms. These complex morphological and physiological characteristics make it hard for regular washing to be effective (Giaouris & Simões, 2018; Gil et al., 2015; Hoagland et al., 2018).

The seriousness of foodborne pathogen contamination of carrots was demonstrated by the recent recalls and outbreaks in the U.S. In July 2021, *Salmonella* contamination was identified in retail packaged carrots, and with early identification and immediate recall, there were no reported outbreaks associated with the contamination. However, in late 2024, contamination of *E. coli* O121:H19 was reported in carrots, which led to an outbreak that started with Grimmway Farms' whole and baby organic carrots, infected 48 individuals in 19 states. Eighteen infected individuals were hospitalized, and one individual succumbed to death. Carrot contamination was found in multiple brands during the outbreak investigation, leading to widespread recalls and increased consumer anxieties about carrot safety (FDA, 2024).

These foodborne disease outbreaks and subsequent carrot recalls are important reminders that the carrot supply chain is vulnerable to contamination with foodborne pathogens, and there is a need for better decontamination methods for this fresh vegetable.

Current Chemical Decontamination Approaches and Limitations

The contemporary fresh produce sector relies on several chemical sanitizers as primary methods of decontaminating fresh produce to ensure its safety. Chlorine-based chemicals, the most common being sodium hypochlorite (NaOCl) at 50-200 ppm, chlorine dioxide (ClO_2) at 1-5 ppm, and other sanitizers such as PAA at 40-80 ppm, and hydrogen peroxide (H_2O_2) at 1-3% concentration are the most sought-after chemical agents to decontaminate fresh produce (Banach et al., 2018; Banach & Van Der Fels-Klerx, 2020; Chen et al., 2018; Joshi et al., 2013; Rodgers et al., 2004; Song & Fan, 2021). Although these treatments effectively reduce microbial loads to more or less varying degrees, the processes prove strictly limiting when used on carrots and other root vegetables (Rajalingam et al., 2021).

The application of these chemical sanitizers often achieves a very limited microbial reduction (typically 1-2 log CFU/g) on produce surfaces (Rodgers et al., 2004). This inefficiency of sanitizers has also been observed in previous research where normal chlorine washing led to a 1.3 log CFU/g reduction of *E. coli* O157:H7 on carrots, which shows the failure of traditional treatments to ensure microbial safety (Dharmarha et al., 2019). One of the major reasons for this limited efficacy in root crops is the rough surface texture, which is a characteristic feature of the skin of carrots and other root vegetables (S. H. Park & Kang, 2017; Ringus & Moraru, 2013; Syamaladevi et al., 2013; Wang et al., 2009). Another reason is the presence of a higher amount of organic matter on the surface of root crops (Gombas et al., 2017; Gurtler et al., 2022; Qadri et al., 2015). These morphological and growth characteristics of root vegetables, such as carrots, allow microorganisms to get better attachment and provide minute crevices for them to hide and grow under. Additionally, these features impede sanitizer contact with the attached microorganisms, and the organic load on the surfaces results in the rapid depletion of sanitizer efficacy due to chemical reactions for neutralization of the active compounds of the sanitizers by the organic compounds.

Aside from efficacy concerns, chemical sanitizers also raise environmental and health considerations when used in higher concentrations. Chlorine-based sanitizers can form potentially carcinogenic disinfection byproducts such as trihalomethanes and haloacetic acids when they react with organic matter (Gil et al., 2009). These toxic effects of chemical sanitizers have triggered several regulatory restrictions on their use globally, with the European Union imposing strict boundaries on the use of chlorine-based sanitizers in the processing of fresh fruits and vegetables and post-harvest uses (EFSA, 2023). With greater consumer awareness of such effects, the inclination has significantly shifted towards fresh produce operations where these chemicals are not applied, thus developing the need for alternative fresh produce decontamination methods (Karst, 2023).

Peracetic acid (PAA) is currently one of the most preferred fresh produce sanitizers due to its improved antimicrobial activity, capacity to act in a wide pH and temperature range, and low generation of toxic by-products compared to chlorinated sanitizers (Haute et al., 2015; Sethi et al., 2020; Stearns et al., 2022). Its wide spectrum of antimicrobial activity against bacteria, viruses, and fungi makes it particularly beneficial for produce surface decontamination (Cano et al., 2021; Zoellner et al., 2018). PAA is usually recommended for its use in concentrations of 40 to 80 ppm, resulting in significant microbial reductions during short contact times of approximately 1 to 5 minutes (Banach et al., 2015; FDA, 2008). Interestingly, PAA does not show a noticeable decline in potency even when there is organic matter present, making it an ideal option to be utilized with root vegetables like carrots that typically contain high loads of organic matter (Haute et al., 2015). Furthermore, due to its rapid biodegradation into harmless by-products such as water, acetic acid, and oxygen, PAA has been found to be an environmentally friendly option to sanitize fresh produce (Méndez-Galarraga et al., 2019).

Ultraviolet Light as an Alternative Decontamination Technology

Electromagnetic radiation with a wavelength range of 100–400 nm is termed UV light. The UV spectrum includes UV-A (315-400 nm), UV-B (280-315 nm), UV-C (200-280 nm), and vacuum-UV (100-200 nm). Of the different types of UV light, UV-C (200-280 nm) is the most promising non-thermal, chemical-free alternative for food decontamination (Kebbi et al., 2020). Its germicidal effect comes from its ability to form thymine dimers, which prevents microbial

DNA from replicating and leads to cell death instead (Goodsell, 2001; Koutchma et al., 2015). Currently, the application of UV-C light on fresh produce has gained more attention because of its effective results in the antimicrobial application, broad spectrum of effectiveness, and its action, which has very limited evidence for the production of any toxic by-products or any negative effect on post-harvest and nutritional attributes of fresh produce (Koutchma et al., 2015). Different versions of this system have gained commercial popularity for treating water, air, and various fruits and vegetables.

There are various factors that affect how well UV light works in inactivating microbes present in fresh produce. It includes the wavelength and dose of the UV light, the type of produce, and the type of microorganism present in the produce (Adhikari et al., 2015; Syamaladevi et al., 2013, 2015). A produce's surface smoothness also seems to play a role, as UV light inactivation tends to work better on a smooth surface as compared with a rough surface texture. A study involving apples, fresh produce with a smooth surface texture, and pears and strawberries, produce with a rougher surface texture showed that with UV-C light at a dose of 0.92 kJ/m^2 was able to show approximately ~3 log CFU/g, ~2 log CFU/g, and ~1 log CFU/g microbial reductions, respectively, in the number of inactivated bacteria present on the fruit's surface (Adhikari et al., 2015).

Historically, traditional UV-C applications in food processing have made use of mercury vapor lamps, showing a very effective approach to microbial control in the food and fresh produce industry. For instance, researchers reported a 3.2 log CFU/g reduction of *Salmonella* Typhimurium on tomato surfaces following exposure to 120 mJ/cm^2 of UV-C light, a significant improvement compared to the 1.8 log reduction achieved by conventional chlorine washing under similar conditions (Mukhopadhyay et al., 2014). Similarly, another study also reported a 2.7 log CFU/g reduction of *Listeria monocytogenes* and a 2.16 log CFU/g reduction of *E. coli* O157:H7 on cucumbers when treated with UV at 800 mJ/cm^2 (Chun et al., 2010). While these were promising results, a significant research gap remains to assess the effectiveness of UV-C treatment and its potential use in combination with sanitizers on root vegetables, particularly carrots.

Decontaminating carrots using UV-C technology can have unique engineering challenges that have no standard solutions. Because of the way such treatments are structured, the surface of fresh produce can produce shadowing effects, meaning that some parts of a carrot might not be evenly exposed to the UV-C light (Koutchma et al., 2015). Another potential problem that carrots have, especially cut carrots or baby carrots, is a very high carotenoid content, which also absorbs UV light (Chandra et al., 2021). Even if the carotenoids are not entirely capable of absorbing the UV-C light, they may still partially do so, thus partially compromising decontamination.

Similarly, chemical sanitizers such as peracetic acid (PAA) and chlorine sanitizers, although extensively used globally, are riddled with uncertainties of reduced efficacy through interference by organic matter, microbial resistance, and failure to penetrate certain fruit and vegetable surfaces (Banach et al., 2015; Gombas et al., 2017). Due to these intrinsic shortcomings in individual sanitation techniques, UV-C combined with chemical sanitizers is an effective future solution. A number of studies have established that such combined treatments synergistically enhance microbial inactivation by complementing the limitations of a single method (Fan et al., 2017; Kang et al., 2024). Not only does this coupled approach remedy unbalanced exposure issues inherent in UV-C treatment, but it also prevents reduced sanitizer performance caused by high organic loads typical of root vegetables. Thus, by integrating UV-C with chemical sanitizers like PAA, a more effective and potent decontamination regimen for carrots and other root crops can be achieved (Lim & Harrison, 2016; Pang & Hung, 2016).

Research Gap and Significance

Despite the growing recognition of the effectiveness of UV-C technology for the disinfection of fresh produce, there are considerable knowledge gaps regarding its application for carrots. First and foremost, the optimum parameters of UV-C dosage, i.e., intensity, exposure time, and wavelength specifically designed for *E. coli* inactivation on carrot surfaces are yet to be established systematically (Koutchma et al., 2015). Second, the relative effectiveness of UV-C treatment versus conventional industry chemical sanitizers (i.e., PAA) for decontaminating carrots is not well delineated. Third, the impact of the surface characteristics of carrots (hydrophobicity, roughness) on the efficacy of UV-C treatment also must be delineated better (Wang et al., 2009; Wei et al., 2017).

Closing these knowledge gaps is imperative for creating evidence-based guidelines for the carrot processing sector in response to recent high-profile outbreaks and growing consumer demand for minimally processed, chemically free foods (Karst, 2023). Studies on new UV-C tunnel technologies for carrot decontamination can have potential applications of improved food safety, increased product shelf life, minimized environmental footprint, and sustained consumer confidence in this highly consumed vegetable. In addition, having established UV-C decontamination methods that can be applied to carrots, this work can be used as a model for other root vegetables encountering the same food safety issues.

Rationale

The rationale of this study in investigating the effectiveness of a novel UV-C tunnel system for *E. coli* decontamination on carrots is multifaceted:

Addressing an important public health need: Recent outbreaks of foodborne disease due to carrots, like the 2024 *E. coli* outbreak that led to 48 illnesses, 20 hospitalizations, and one death across 19 states, illustrate the urgent need for effective decontamination techniques that can be used for carrots.

Improvement of chemical sanitizing in carrots: The most common method for decontaminating carrots involves the application of sanitizers. PAA is regarded as a superior chemical sanitizer because of its effectiveness and due to the lack of formation of harmful byproducts. However, for carrots, if PAA is used at the recommended dose which is 40-80 ppm for dip-washing of carrots, the bacterial reduction is less effective as compared to other fresh produce, as it achieves only a 1-2 log reduction. This limited effectiveness on carrots is due to their surface topography and organic load accumulation in wash water which reacts with the active agent (Dharmarha et al., 2019; Wang et al., 2022). A better approach to the application of PAA sanitizer through the use of a spraying method inside this decontamination tunnel can overcome these limitations.

Meeting consumer and regulatory trends: Heightening regulatory ceilings on the application of chemical sanitizers and growing consumer interest in less processed, chemical-free products necessitate the development of new decontamination technologies that maintain safety and quality traits (EFSA, 2023; Karst, 2023).

Objectives

The overall goal of this study was to evaluate the efficiency of a novel UV-C tunnel system in reducing *Escherichia coli* contamination on whole carrots (Daucus carota). In order to fulfill this objective, the study was grounded in the following specific goals:

1. To compare the microbial reduction effectiveness (log reduction) among different treatments, including UV-C treatment, PAA application, and combined UV-C + PAA application.

2. To determine whether combination treatment offers significantly greater microbial reduction than single treatments.

Materials and Methods

Experimental Design

In this study, a randomized controlled experimental design was employed to compare the effectiveness of different decontamination treatments in minimizing *Escherichia coli* on whole carrots. A custom-designed tunnel conveyor belt system with UV light modules and sanitizer dispensing systems was utilized to establish the antimicrobial efficacy of single and combinative treatments.

Materials and Equipment

Decontamination Tunnel System

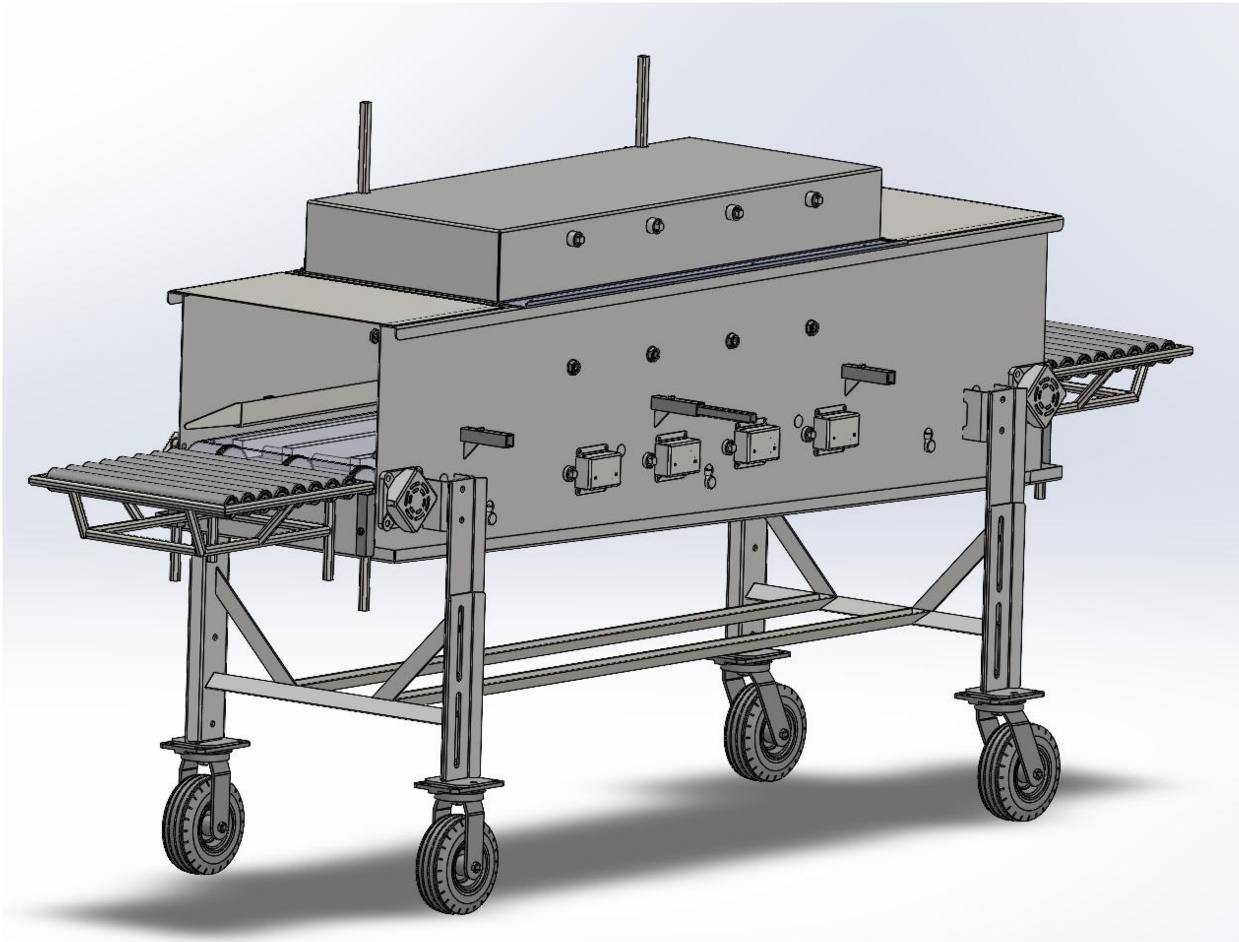

Figure 3.1. Side view of the Decontamination Tunnel System

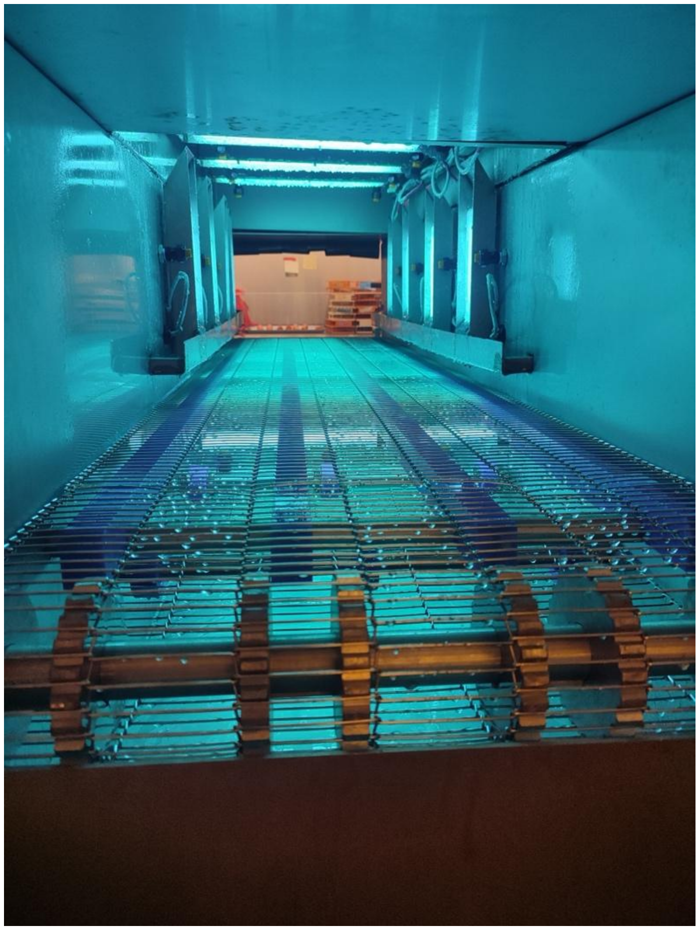

Figure 3.2. Inside View of the Decontamination Tunnel System

The treatment tunnel consisted of four identical treatment modules in sequence on a conveyor belt system. Each module had:

- One 95-watt UV light (Philips TUV PL-L 95W Hg lamp)
- One 65-watt UV light (Philips TUV PL-L 65W Hg lamp)
- Two 30-watt UV lights (Philips TUV PL-L 30W Hg lamp)
- Sanitizer dispensing system with seven aerosol nozzles

In every module, the UV light and the sanitizer dispensing system operated independently, so each module was controllable separately. The modular configuration made flexible configuration possible, e.g., simultaneous or sequential treatment of UV-C light and sanitizer applications. The conveyor belt positioned in the tunnel caused the distances from the UV-C lamps to be different: 40 cm from the top lamps, 6 cm from the bottom lamps, and 18 cm from the side lamps. The power setting of the UV-C lamps also differed in wattage, and this variation was deliberate, considering the different distances and the potential interference created by the conveyor system, most significantly at the lower end, where a higher-watt lamp was used to provide suitable UV exposure despite the interference. The conveyor belt speeds were adjustable and, in this study, were adjusted to provide one minute of total treatment time for each carrot through the tunnel system.

Bacterial Strain and Culture Media

E. coli ATCC 25922 rifampicin-resistant was used as the target pathogen in this study, which is a non-pathogenic, Biosafety level 1 surrogate of pathogenic *E. coli* strains like *E. coli* O157:H7 and other Shiga Toxin-producing *E. coli* (STEC) strains like O26, O45, O103, O111, O121, and O145, which are well-known causative agents of fresh produce contamination (Cheng et al., 2020). The carrots were store-bought, which might contain different background microflora. A rifampicin-resistant strain of *E. coli* ATCC 25922 was used to ensure that only the inoculated microbial strain was enumerated. This allowed selective recovery on tryptic soy agar supplemented with rifampicin and reduced interference of the indigenous microbiota. The culturing media used were Tryptic Soy Agar (TSA) supplemented with rifampicin, Tryptic Soy Broth (TSB) supplemented with rifampicin, Buffered Peptone Water (BPW) at a concentration of 0.1%, and 1X Phosphate Buffered Saline (PBS).

Rifampicin solution was prepared by dissolving 4.8 g of rifampicin (Tokyo Chemical Industry, CAS RN: 13292-46-1) in 40 mL of methanol, and 4.5 mL of this solution was incorporated into 1000 mL of TSA (Soybean-Casein Digest Agar Medium, BD Diagnostic Systems) to achieve the working concentration.

Sample Preparation

Whole fresh carrots were purchased from a local Walmart store to ensure consistency with the products available in most consumer goods stores. Each carrot was weighed to obtain a standard weight of 100 ± 10 grams, trimmed to remove the leafy crown portion to prevent any likely interference due to leafy area and reduce surface area heterogeneity exposed to treatments, and visually examined for uniformity and defects such as cracks on the carrots.

Bacterial Inoculation Protocol

Culture Preparation

The rifampicin-resistant *E. coli* ATCC 25922 was transferred from frozen glycerol stock by utilizing sterile inoculation loops. A master plate was created on TSA supplemented with rifampicin and incubated at 35°C for 24 ± 1 hours. Subculture 1 (SC1) was prepared by inoculating one colony from the master plate into 10 mL of TSB (Trypticase Soy Broth, BD Diagnostics Systems) with rifampicin using sterile inoculating loops and incubating at 35°C for 24 ± 1 hours. Subculture 2 (SC2) was prepared by inoculating 100 µL of SC1 into 30 mL of TSB with rifampicin and incubating at 35°C for 24 ± 1 hours.

Inoculum Preparation and Standardization

SC2 was centrifuged for 10 minutes at 10,000 RPM, and the pellet was washed twice with 1X PBS diluted from 10X PBS (Phosphate Buffered Saline, 10X Solution, Fisher BioReagents) through repeated centrifugation. The final pellet was resuspended in 30 mL of PBS to make the concentrated inoculum. For carrot inoculation, 120 mL of concentrated inoculum was diluted to 480 mL with PBS to achieve the working inoculation solution.

Carrot Inoculation Process

Prepared carrots were inoculated according to a dip-inoculation procedure. The carrots were fully immersed in the inoculation solution for 10 minutes inside a whirl-pack bag. Inoculated carrots were allowed to dry in a biological safety cabinet for 1 hour until they were completely dry. This drying time permitted bacterial attachment without cross-contamination.

Treatments

Peracetic Acid (PAA)

To treat carrots with PAA, commercial PAA from SaniDate 5.0 (Biosafe Systems, LLC, East Hartford, CT) (EPA Reg. No. 70299-19) was used. The PAA had 23.0% hydrogen peroxide and 5.3% peroxyacetic acid as active ingredients to decontaminate *E. coli*.

To prepare an 80 ppm PAA working solution, 146.7 mL of the concentrated sanitizer was transferred to a clean, sterile container that contained 30 gallons (approximately 113.6 L) of distilled water. After mixing the sanitizer, PAA chemkey reagents (0.04 - 50.0 mg/L PAA) and a Hach SL1000 Portable Parallel Analyzer (PAA) meter were used to determine the concentration of sanitizer to ensure that the required concentration was achieved. Before and during treatment application, the concentration readings were taken to make sure that the target of 80 ppm was reached and maintained.

The concentration of PAA (i.e., 80 ppm) was selected based on the current guidelines for industrial use on fresh produce by FDA (21 C.F.R. § 173.315, 2023). The PAA working solution was used by spraying through the in-built nozzles within all four modules of the tunnel.

Ultraviolet (UV) light treatment

For the UV treatment, four UV-C lamps (254 nm) were used per module based on the type of treatment. The height of the lamps and the conveyor speed (60±3 seconds) were adjusted to ensure identical exposure to the samples.

To check the intensity of UV-C during treatment, an ILT 2400 UV radiometer (International Light Technologies) was passed through the UV tunnel. The equipment was used to measure the real-time irradiance (W/cm^2) approximately every second throughout the treatment time. The data were exported and analyzed using R statistical software to determine both intensity profile and total UV-C dosage.

The level of the conveyor belt within the tunnel was fixed by its build and had varying distances from the UV-C lamps on top (40 cm), bottom (6 cm), and sides (18cm), as well as because of the variation in the power of the lamps on top (60-watt), bottom (95-watt), and two on each side (30-watt), the UV exposure on each side was different. Based on this setup, different dosages were calculated on each side. The dosage was determined by multiplying the measured UV intensity by the exposure time, converting it to millijoules per square centimeter (mJ/cm^2).

Table 3.1. Varying UV-Dosage Across Different Directions Inside the Decontamination Tunnel in Two Treatments Using UV-C Lamps

Treatment Type	UV Dose (Bottom)	UV Dose (Top)	UV Dose (Left)	UV Dose (Right)	Average
4 modules	184 mJ/cm^2	117 mJ/cm^2	52.9 mJ/cm^2	43.5 mJ/cm^2	99.35 mJ/cm^2
2 modules (2 & 4)	69.6 mJ/cm^2	46.2 mJ/cm^2	32.3 mJ/cm^2	24.7 mJ/cm^2	43.2 mJ/cm^2

For the UV treatment with all four modules, the average intensity during the treatment period was 1.66×10^{-3} W/cm^2, and the average UV dose throughout exposure time was approximately 99.35 mJ/cm^2. For the combination treatment that used two modules (Module 2 and 4), the average intensity was 7.2×10^{-4} W/cm^2 during the treatment period, and the average UV dose throughout exposure time was approximately 43.20 mJ/cm^2.

$$\text{UV Dose } (mJ/cm^2) = \text{UV Intensity } (mW/cm^2) \times \text{Exposure Time (seconds)}$$

Treatment Applications

Four treatment conditions were tested:

1. Control: Carrots were moved through the tunnel system with no UV lights on and no sanitizer application
2. Peracetic Acid (PAA) Treatment: Carrots were exposed to 80 ppm PAA solution sprayed through all four nozzle modules at a rate of 0.83 gallons per minute from each module.
3. UV Treatment: Carrots were exposed to all four UV light modules with no sanitizer treatment
4. Combined Treatment: Initial pilot testing indicated that activating all four sanitizer units produced a dense PAA mist, resulting in the scattering and absorption of UV-C light, which diminished the effectiveness of the disinfection process due to shadowing and aerosol interference. To address this limitation, split-modular configuration was used in this study, in which only two sanitizer units were used and two UV units were used across the four modules at every cycle of treatment, in which the sanitizer unit was activated first before exposure to UV lights to allow PAA pre-rinse not just to decontaminate but also to loosen and dislodge attachment of E. coli and, hence, increase exposure to the following UV-C treatment. So, alternating PAA and UV treatment with modules 1 and 3 providing PAA (80 ppm) and modules 2 and 4 providing UV exposure was used.

Each treatment was applied for a standard duration of 60 seconds as carrots moved through the tunnel on the conveyor belt system.

Bacterial Recovery and Enumeration

Sample Processing

Each carrot was dropped immediately into a sterile Whirl-Pak bag containing 100 mL of 0.1% BPW (Buffered Peptone Water Pre-enrichment, BD Diagnostics) following treatment. The bag was massaged by hand for one minute to facilitate the recovery of bacteria from the carrot surface to the recovery medium.

Serial Dilution and Plating

Ten-fold serial dilutions were prepared from the recovery medium in order to obtain countable colony numbers across the expected range of bacterium reduction. The undiluted recovery medium and serial dilutions were plated on TSA supplemented with rifampicin via standard spread-plating techniques.

Incubation and Colony Enumeration

Plated samples were incubated at 35°C for 24 ± 1 hour. After incubation, colonies were counted using standard colony counting procedures. Results were expressed as log CFU/g after adjusting for appropriate dilution factor corrections.

Statistical Analysis

Statistical analysis was performed with the R statistical package (version 025.05.1-513). Colony-forming units per milliliter (CFU/g) were log-transformed to normalize the data distribution and stabilize variances. A linear mixed-effects model was fit to the log CFU/g values, and treatment efficacy was evaluated by calculating the log reduction values relative to the control. In this, the treatments were considered fixed effects, and trials were random effects. The pairwise comparisons among treatments were similarly assessed with Tukey's Honest Significant Difference (HSD) test with a significance level of $\alpha = 0.05$. The model satisfied the assumptions of normality and homogeneity of variance as confirmed by Q-Q plots and residual plots.

Quality Control and Validation

The control treatment consisted of inoculated carrots passed through the tunnel system with no UV lights activated and no sanitizer application, serving as the baseline for comparison with treated samples.

The study was a Randomized Complete Block Design (RCBD), which consisted of three independent trials serving as blocks. For each trial, the whole carrots were randomly assigned to one of four treatments: Control, PAA, UV, and PAA+UV. The carrots were randomly placed on the tray, and each carrot was assigned to a treatment group through randomized selection of treatment groups to ensure that each treatment had an equal chance of representing variations in carrot size, inoculum adhesion, and handling conditions. Each trial incorporated three biological replicates (three single carrots) per treatment group. The experiment was performed in triplicate (three independent trials), providing a total of nine observations within each treatment group (n=9). The replication method applied provided adequate statistical power to detect notable differences in bacterial reduction between treatment groups.

All microbiological manipulations were performed in the appropriate biological safety cabinets at Bhullar Food Safety Lab (BSL-2 lab) in accordance with institutional biosafety regulations. All contaminated items were discarded appropriately after proper autoclaving or treatment with sanitizer, and personal protective equipment was used throughout the experimental procedures.

Results

The objective of the study was to use a novel decontamination tunnel system to test for the effectiveness of UV, PAA, and a combination of UV with PAA, to minimize *E. coli* microbial load on whole carrots to establish the most suitable decontamination process. For comparison of the decontamination efficiency of UV-C, peracetic acid (PAA), and combination, log reduction values for *Escherichia coli* ATCC 25922 were calculated compared to the control group. A linear mixed-effects model with treatment as a fixed effect and trial as a random effect to adjust for trial variation was used. The model diagnostics showed normality of the microbial reduction data and equal variances within the assumptions held, thereby confirming robust statistical inference.

For studying the effectiveness of three treatment types, the untreated control (inoculated with *E. coli)* was used as a baseline for assessing microbial reduction (Figure 3.3). The combined UV+PAA treatment registered the highest mean log reduction (2.83 ± 0.10), followed by that of PAA alone (2.38 ± 0.06), and UV alone (1.49 ± 0.16). The treatments lowered *E. coli* counts on carrot surfaces, but at varying levels (Table 3.2).

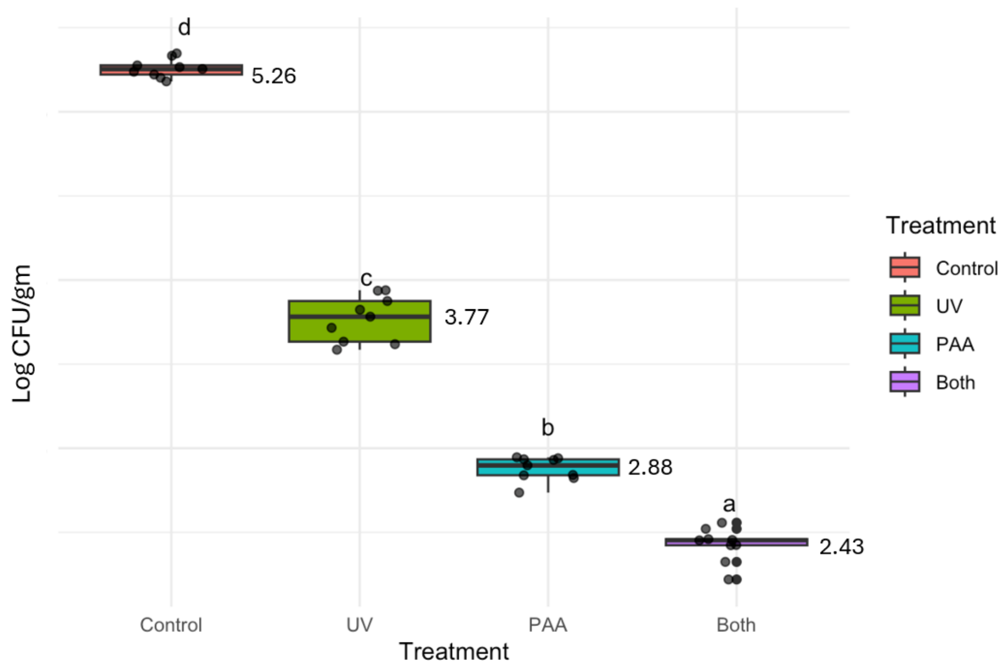

Figure 3.3. Boxplot with the Distribution of E. coli Log Values Across Treatments

The linear mixed model analysis provided a statistically significant treatment effect ($p < 0.001$), with negligible variation attributable to trial effects (variance = 0.00036), meaning the type of decontamination strategy significantly affected microbial reduction. Estimated marginal means and 95% confidence intervals for groups are given in Table 3.2. The combined treatment group resulted in the highest level of microbial inactivation, significantly superior to the single treatment.

Table 3.2. Estimated Marginal Means ± SE and 95% Confidence Intervals for Log Reduction by Treatment

Treatment	**Mean Log reduction (CFU/g)**	**Standard deviation**	**n**	**95% Confidence Interval**
UV	$1.49^{a} \pm 0.038$	0.16	9	1.38 – 1.60
PAA	$2.38^{b} \pm 0.038$	0.06	9	2.27 – 2.49
Both (UV+PAA)	$2.83^{c} \pm 0.038$	0.10	9	2.72 – 2.94

Estimated marginal means with standard errors and 95% confidence intervals for each treatment group were obtained from a linear mixed-effects model with treatment as a fixed effect and trial as a random effect. Different superscript letters indicate statistically significant differences among treatments based on Tukey's HSD test ($\alpha = 0.05$).

Tukey's Honest Significant Difference (HSD) test also confirmed that comparisons between treatment groups were statistically different ($p < 0.0001$), as shown in Table 3.3. The difference between PAA and UV treatments in log reduction was 0.891, while that between UV and combined treatment was 1.341. A smaller but still significant difference (0.450) was observed between PAA and the combined treatment, also corroborating the presence of a synergistic effect when UV and PAA were given together.

Table 3.3. Tukey HSD Pairwise Comparisons of Log Reduction Between Treatments

Comparison	**Mean Difference**	**Std. Error**	**t-ratio**	**p-value**
PAA vs UV	0.891	0.052	17.17	<0.0001
(UV+PAA) vs UV	1.341	0.052	25.84	<0.0001
(UV+PAA) vs PAA	0.450	0.052	8.67	<0.0001

Pairwise comparisons of treatment mean using Tukey's HSD test. Reported are the mean differences, standard errors, t-ratios, and p-values. All comparisons were statistically significant at $p < 0.0001$.

Collectively, these findings establish that all treatments significantly reduce *E. coli* contamination on whole carrots compared to the untreated control baseline. The combined UV+PAA treatment resulted in the greatest reduction (2.83 log CFU/g), which indicates synergy between physical and chemical decontamination treatments. PAA alone was very effective with a

2.38 log reduction, while UV alone had relatively lower effectiveness. These results suggest that while UV and PAA alone produce noteworthy reductions, in combination, they are much more effective and may have the potential to present a promising means for enhancing microbial safety in root vegetable processing systems.

Discussion

The findings of the study show that this newly designed tunnel that incorporates the combined application of UV and sanitizers can serve as an effective novel equipment for the decontamination of fresh produce. Each treatment used in the study, UV-C light (254nm), PAA (80 ppm), and a combination of PAA and UV in alternating modules, can significantly reduce *E. coli* contamination on whole carrots. These results are also supported by previous research on the poor efficacy of traditional chemical sanitizers and the significantly higher efficacy of treatments using their combination with UV-C light (Fan et al., 2017; Rajalingam et al., 2021). From all the treatments studied, the most effective treatment was combined UV+PAA, with a reduction of 2.83 log CFU/g of *E. coli* from the control. Although not additive, the combined effect of these two methods seems to be supplementing one another.

This study noted substantial but comparatively minor microbial reductions when using UV-C treatment by itself (1.49 log CFU/g). This is most likely due to the inherent rough surface texture of carrots and the high carotenoid content of the metabolically optimized, high-cell-wall carrot cultivars used in this work. This is a consistent finding across several studies that have explored the use of UV-C light for inactivation of pathogens, which has noted that the efficacy of UV-C light is reduced when it comes to irregular surfaces (Syamaladevi et al., 2013; Wang et al., 2009) and with materials that are good UV absorbers such as carotenoids (Chandra et al., 2021). This limitation emphasizes the necessity of adjusting UV-C application parameters, such as increasing exposure time or employing multidirectional exposure setups, to improve decontamination efficacy (Koutchma et al., 2015).

The combination of UV and PAA (peracetic acid) yielded significantly improved microbial reductions compared to UV alone. This effect was similar to those reported by researchers in fresh produce applications (Lippman et al., 2020; Ortiz-Solà et al., 2022). These findings suggest that combined treatment strategies could address the contamination problems associated with carrots. The evidence could also apply to other root vegetables with similar surface properties.

Even though the results were promising, several practical challenges remain for large-scale applications. Further evaluation is still needed to determine the economic feasibility and the optimization of treatment parameters (exposure times, dosage, and conveyor speed, for instance), and to assess the overall compatibility of UV light with current processing systems. Thus, the likely scenario is that the future UV-C user will first be a consumer of ready-to-eat packaged carrots and other peeled root vegetables processed under conditions that are safe and favorable to the human consumer, first because those conditions satisfy food safety standards, then because they also address repercussions of increasingly strict regulatory requirements the use of chemical sanitizer in directly consumed fresh produce (EFSA, 2023; Karst, 2023).

Limitations of the Study

This research was done in a laboratory with tightly controlled conditions. To ensure that the results can be applied in the real world, further experiments are needed in commercial processing settings that closely mimic everyday conditions. Additionally, the application of UV-C light varied between different exposure sides, which limits the overall generalizability of the results. Therefore, studying the effectiveness of more consistent exposure in the future could aid in commercial scalability. The economic aspects demand comprehensive study, especially the cost-effectiveness and practical integration of UV-C technology into pre-existing processing lines.

Conclusion

This research highlights the potential of a new system, consisting of a tunnel and UV-C light, for decontamination of foodborne pathogens on the surface of carrots. The use of PAA in conjunction with this UV-C light treatment appeared to create an even more effective combination than using either treatment alone. So, for fresh produce and the carrot in particular, the application of UV-C light by retrofitting the lights in already existing packaging lines in the fresh produce and carrot industries certainly could be part of the next step in moving toward more chemical-free alternatives for ensuring the safety of ready-to-eat fresh produce.

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Appendix A - Interview Question

Appendix Table A.1. Key Questions for Needs Assessment of Refugee Growers

Topics	Questions
Biological Contamination Risks	What do you think are potential sources of contamination on your farm or any farm in general?
Worker Health and Hygiene	When other people who do not generally work at your farm come to visit or volunteer for help, what instructions do you share with them to ensure produce safety?
	What do you do if someone who works on your farm becomes ill or has symptoms of being ill? Are there specific procedures in place?
Soil Amendment	In your opinion, what are the potential risks associated with using soil amendments?
	Can you give examples of things you do during the application of these amendments to ensure produce safety?
Agricultural Water	What are the primary sources of water used on your farm?
	For water used in washing fruits and vegetables, how often do you change the wash water?
	Do you test the quality of water used on the farm? If yes, how?

Appendix B - Evaluation Surveys

Appendix Table B.1. Evaluation Survey: Management of Sick Farm Workers on Produce Farms

	Constructs	Strongly Disagree	Disagree	Agree	Strongly Agree
	Intention				
1.	I plan to tell my farm supervisor about my health condition when I am sick.	❑	❑	❑	❑
2.	I plan to stay home until I no longer have any signs of sickness.	❑	❑	❑	❑
3.	I plan to avoid handling produce on the farm when I am sick.	❑	❑	❑	❑
4.	I plan to work away from my coworkers on the farm when I am sick.	❑	❑	❑	❑
	Perceived Behavioral Control				
5.	Informing my farm supervisor if I'm sick is possible for me to do.	❑	❑	❑	❑
6.	Taking sick leave from the farm to stay at home when I am sick is possible for me to do.	❑	❑	❑	❑
7.	When I am sick, it is possible for me to work in areas away from produce.	❑	❑	❑	❑
8.	When I am sick, it is possible for me to work in areas away from my coworkers.	❑	❑	❑	❑
	Subjective Norms				
9.	My farm supervisor expects me to let them know when I have any signs of sickness.	❑	❑	❑	❑
10.	My farm supervisor expects me to stay at home when I am sick.	❑	❑	❑	❑
11.	My coworkers expect me to stay at home when I am sick.	❑	❑	❑	❑
12.	My farm supervisor expects me not to touch produce on the farm when I am sick.	❑	❑	❑	❑
	Attitude				
13	Farm workers working on the farm with produce while showing signs of sickness is unsafe.	❑	❑	❑	❑
14	Farm supervisors knowing about sick workers' health is necessary.	❑	❑	❑	❑
15	Sick farm workers should stay at home to keep the produce safe at the farm.	❑	❑	❑	❑
16	Sick farm workers working on farms near healthy workers are harmful to coworkers' health.	❑	❑	❑	❑

Appendix Table B.2. Evaluation Survey: How to Control Germs from Animals on the Farm

	Constructs	Strongly Disagree	Disagree	Agree	Strongly Agree
	Intentions				
1.	I plan to have farm rules for people who visit my farm.	❑	❑	❑	❑
2.	I plan to inform farm visitors about produce safety practices on my farm.	❑	❑	❑	❑
3.	I plan to use visual materials (like posters/handouts) to share farm rules with the visitors.	❑	❑	❑	❑
4.	I plan on restocking handwashing supplies used by the farm visitors.	❑	❑	❑	❑
	Perceived Behavioral Control				
5.	Informing farm visitors about produce safety practices on my farm is possible for me to do.	❑	❑	❑	❑
6.	Managing visitor access in different areas on the farm is possible for me to do.	❑	❑	❑	❑
7.	Having handwashing facilities accessible to visitors is possible for me to do.	❑	❑	❑	❑
8.	Having toilet facilities accessible to visitors is possible for me to do.	❑	❑	❑	❑
	Subjective Norms				
9.	Farm visitors expect me to tell them my farm's produce safety practices.	❑	❑	❑	❑
10.	Farm visitors expect me to tell them what areas they can visit within the farm.	❑	❑	❑	❑
11.	My farm supervisors expect me to tell farm visitors what areas they can visit within the farm.	❑	❑	❑	❑
12.	Farm visitors expect me to provide them with toilet facilities.	❑	❑	❑	❑
	Attitude				
13	Farm rules for visitors are important.	❑	❑	❑	❑
14	Knowing whether farm visitors are healthy is important.	❑	❑	❑	❑
15	Not allowing visitors into produce storage areas is beneficial.	❑	❑	❑	❑
16	Handwashing facilities for farm visitors are necessary.	❑	❑	❑	❑

Appendix Table B.3. Evaluation Survey: How to Control Germs from Animals on the Farm

	Constructs	Strongly Disagree	Disagree	Agree	Strongly Agree
	Intentions				
1.	I plan to monitor the produce farm for signs of animal-related germs.	❑	❑	❑	❑
2.	I plan to use tools to keep animals away from the produce farm. (Tools are defined as scarecrows, fences and noise devices)	❑	❑	❑	❑
3.	I will not harvest produce that has signs of animal-related germs.	❑	❑	❑	❑
4.	I plan to keep records of the events of animal-related germs on the produce farm.	❑	❑	❑	❑
	Perceived Behavioral Control				
5.	Monitoring the produce farm for signs of animal-related germs is possible for me to do.	❑	❑	❑	❑
6.	Preventing animals from entering the produce farm is possible for me to do.	❑	❑	❑	❑
7.	Creating no-pick zones around produce areas with signs of animal-related germs is possible for me to do.	❑	❑	❑	❑
8.	Cleaning tools used to collect dead animals is possible for me to do.	❑	❑	❑	❑
	Subjective Norms				
9.	My customers value me providing safe produce that is free of germs.	❑	❑	❑	❑
10.	My farm supervisor approves of my efforts to prevent animal-related germs on produce farms.	❑	❑	❑	❑
11.	My farm supervisor supports me making a no-pick zone near animal poop on produce farm.	❑	❑	❑	❑
12.	My farm supervisor supports me disposing of dead animals from the farm.	❑	❑	❑	❑
	Attitude				
13	Keeping animals away from produce on the farm is a good produce safety practice.	❑	❑	❑	❑
14	Monitoring produce growing areas for signs of animal-related germs is a good produce safety practice.	❑	❑	❑	❑
15	Separating produce eaten by animals from good produce is a good produce safety practice.	❑	❑	❑	❑
16	Harvesting produce that is near animal poop is NOT a good produce safety practice.	❑	❑	❑	❑

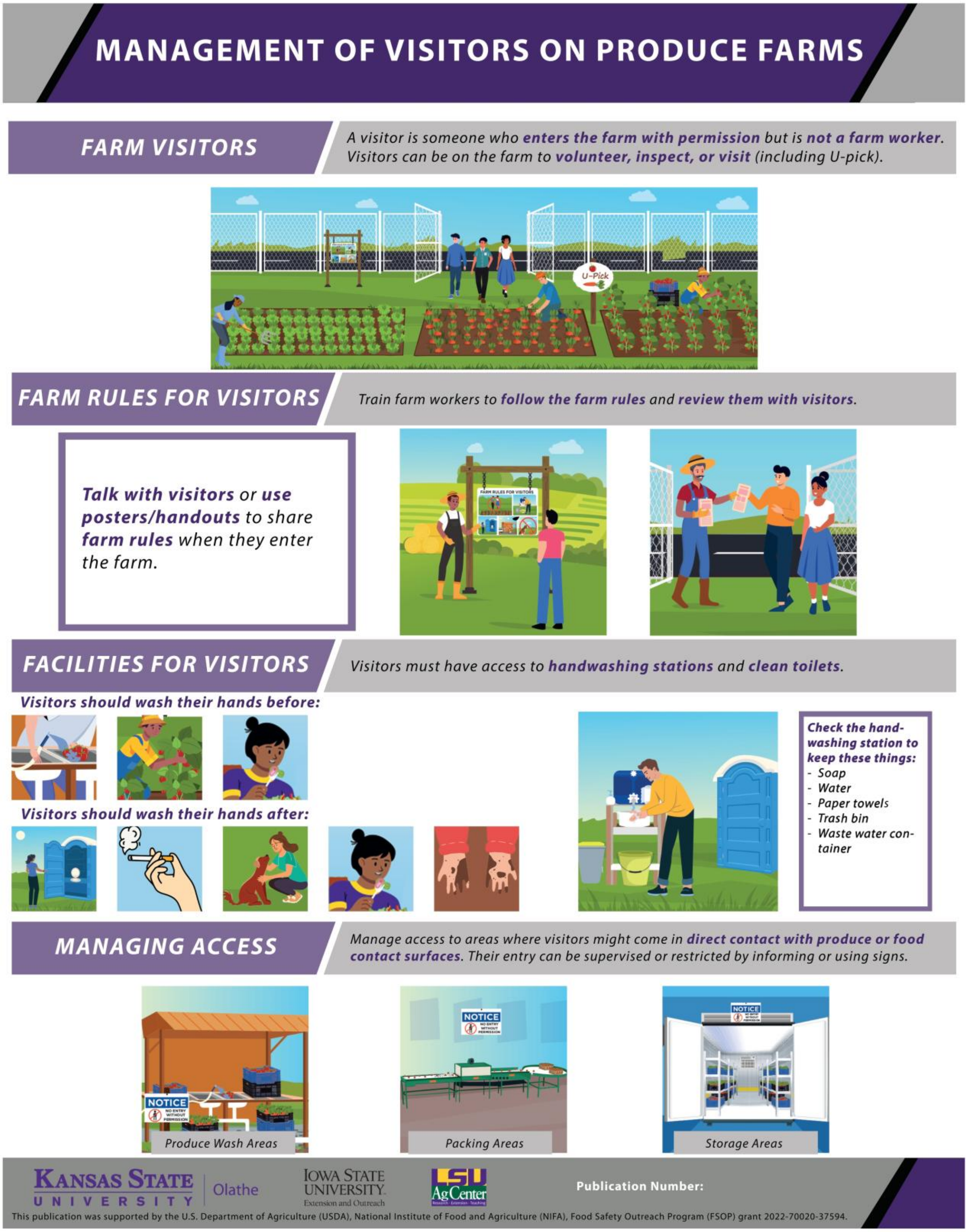
Appendix Table B.4. Evaluation Survey: Understanding Fertilizers and Their Risks

	Constructs	Strongly Disagree	Disagree	Agree	Strongly Agree
	Intentions				
1.	I will NOT use untreated fertilizers from animal sources on fresh produce close to harvest date.	❑	❑	❑	❑
2.	I plan to follow a 90-day untreated fertilizer application interval for crops that have edible portions that do NOT touch soil.	❑	❑	❑	❑
3.	I plan to follow a 120-day untreated fertilizer application interval for crops that have edible portions that touch the soil.	❑	❑	❑	❑
4.	I plan to keep records of the fertilizers used on the farm.	❑	❑	❑	❑
	Perceived Behavioral Control				
5.	NOT applying untreated fertilizers on fresh produce is possible for me to do.	❑	❑	❑	❑
6.	Following the 90-day application interval when untreated fertilizer is used on crops with an edible portion that does NOT touch the soil is possible for me to do.	❑	❑	❑	❑
7.	Following the 120-day application interval when untreated fertilizer is used on crops with an edible portion that touches the soil is possible for me to do.	❑	❑	❑	❑
8.	Keeping accurate records of fertilizers used on the farm is possible for me to do.	❑	❑	❑	❑
	Subjective Norms				
9.	My community values me using safe using proper fertilizer application interval.	❑	❑	❑	❑
10.	My farm supervisor supports me following a 90-day untreated fertilizer application interval for crops that have edible portions that do NOT touch the soil.	❑	❑	❑	❑
11.	My farm supervisor supports me following a 120-day untreated fertilizer application interval for crops that have edible portions that touch the soil.	❑	❑	❑	❑
12.	My farm supervisor supports me keeping accurate records of the fertilizers used on the farm.	❑	❑	❑	❑
	Attitude				
13	Applying untreated fertilizer close to harvest date is NOT a good produce safety practice.	❑	❑	❑	❑

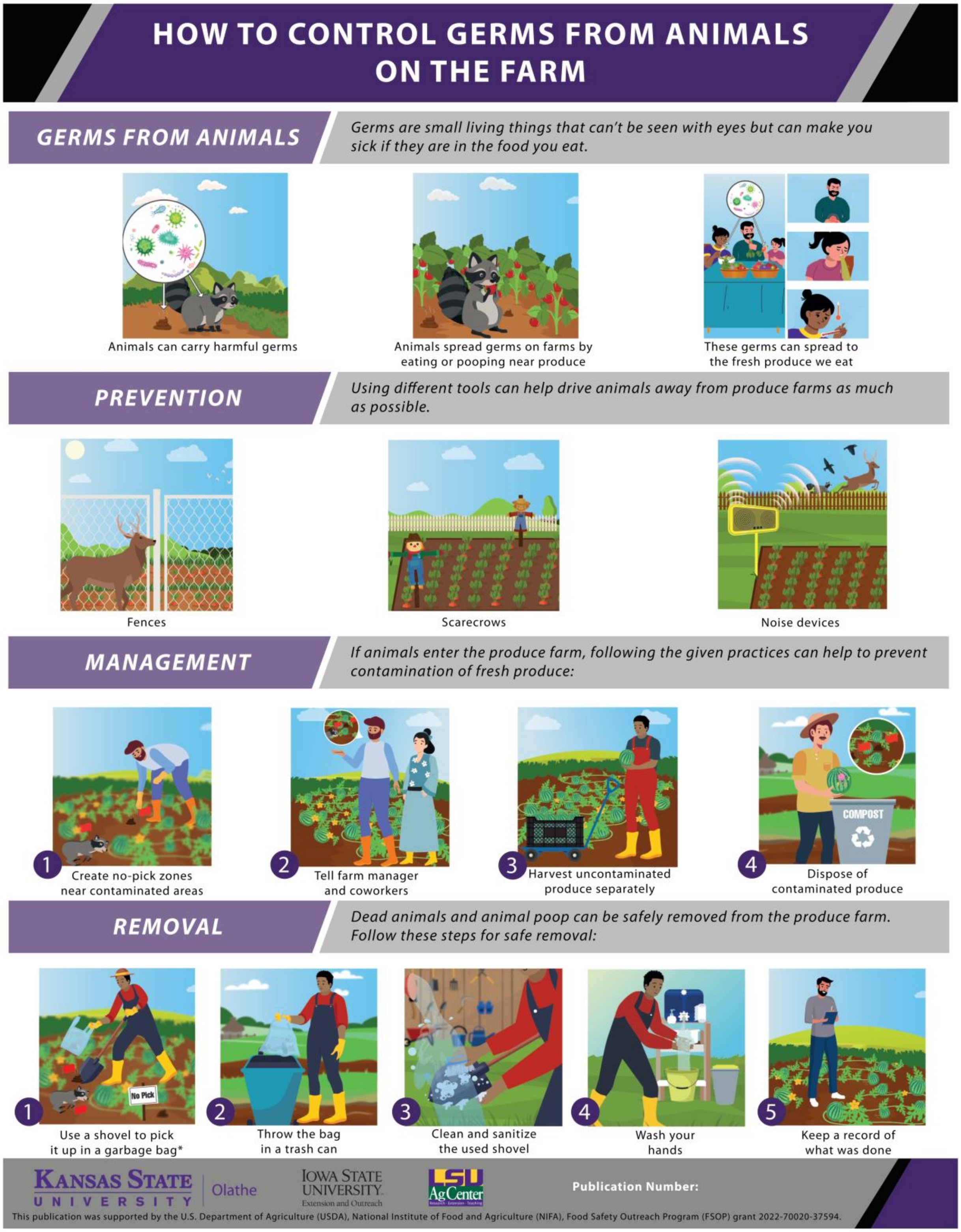
14	Delaying the harvest of produce where untreated fertilizers are used is a good produce safety practice.	❑	❑	❑	❑
15	Keeping records of fertilizers stored on the farm is a good produce safety practice.	❑	❑	❑	❑
16	Keeping records of fertilizers used on the farm is a good produce safety practice.	❑	❑	❑	❑

Appendix C - Produce Safety Posters

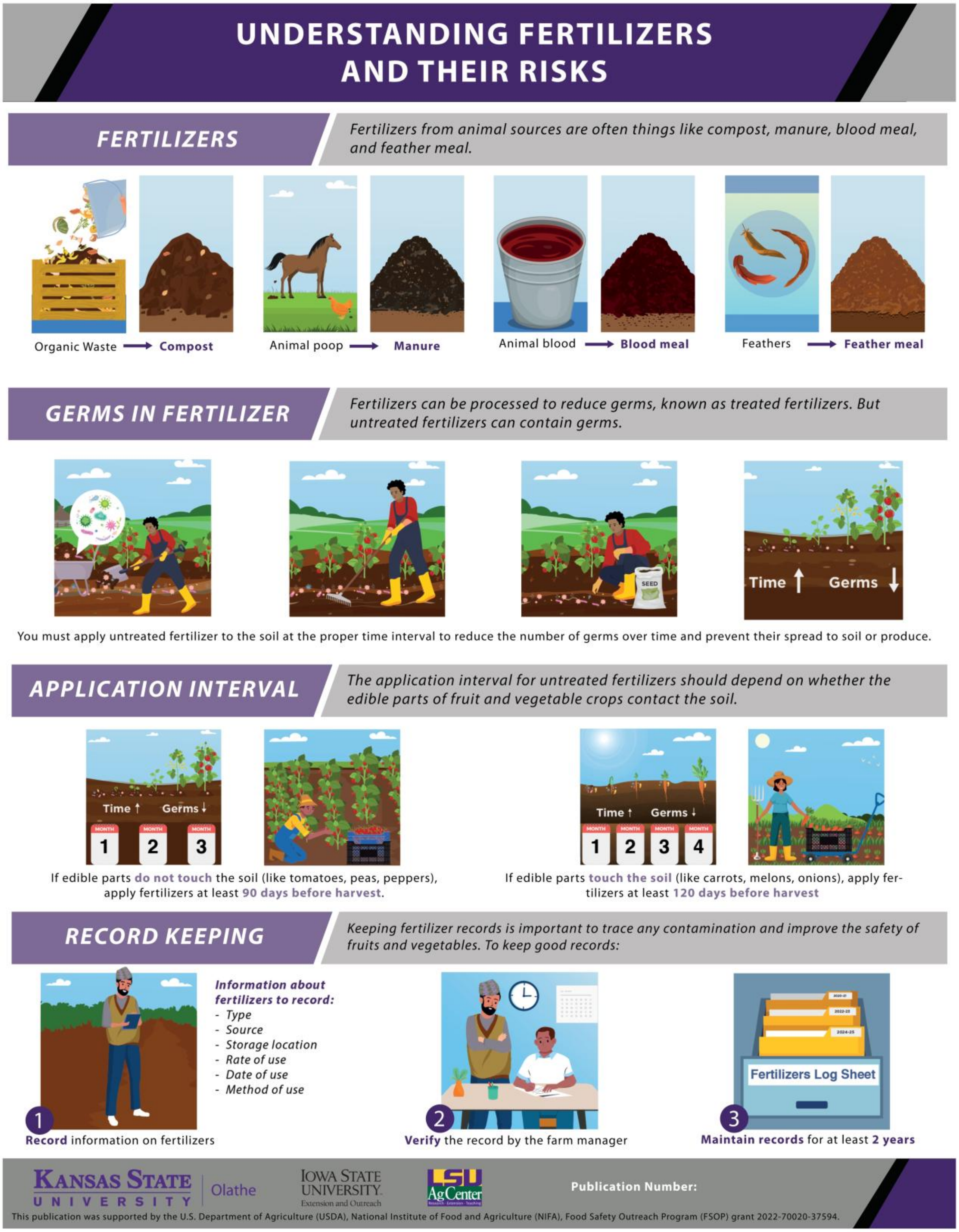
Appendix Figure C.1. Poster 1: Management of Sick Farmworkers



Appendix Figure C.2. Poster 2: Management of Visitors on Produce Farms



Appendix Figure C.3. Poster 3: How to Control Germs from Animals on the Farm



Appendix Figure C.4. Poster 4: Understanding Fertilizers and their Risks