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Knowledge, Attitudes, and Perceptions of UV-C Light Technologies for Agricultural Surface Water Decontamination by Produce Growers in Kansas and Missouri

ABSTRACT

UV-C light technology is used extensively for drinking water treatment but has yet to become popularized in fresh produce production in the central United States. Thus, it is imperative to investigate the major drivers for UV-C adoption (or lack thereof) by produce growers. A survey instrument was designed to determine factors that most impact the attitudes of fresh produce growers (n = 82) in Kansas and Missouri toward the adoption of UV-C technology for agricultural water treatment. Grower knowledge of UV-C light was measured by using five close-ended constructs evaluated on a binary scale (where 1 = correct; 0 = incorrect). An overall attitude score was calculated from eight constructs by using a 5-point Likert scale (strongly agree to strongly disagree). The data indicated a large variation in grower knowledge of UV-C (mean = 2.61; standard deviation = 1.32). Stepwise regression (n = 62) revealed that the overall attitudes were most influenced by grower knowledge of UV-C (P < 0.0001), farm size (P = 0.0199), farm income (P = 0.1047), and state (P = 0.1237). Growers perceived cost (27 of 81, 33.3%) and technical skills (25 of 81, 30.9%) as major barriers to UV-C light implementation, and 34.6% (28 of 81) felt the technology was not appropriate for their operation. These data improve the current understanding of different factors that could impact produce grower adoption of UV-C technologies for agricultural water decontamination.

INTRODUCTION

Water is a critical factor for microbial contamination due to the history of water-related foodborne outbreaks in horticultural commodities, such as leafy greens *(19)*. Such outbreaks disproportionately occur from operations using surface waters, which carry a higher microbial risk in fresh produce operations, as it is usually not feasible to isolate these water sources from environmental contamination (i.e., wildlife or other animals) *(37)*. Chemical sanitizers (i.e., sodium hypochlorite) are widely recognized interventions in the fresh produce industry to reduce pathogens in agricultural surface water *(7)*. However, degradation by-products of chemical sanitizers can have negative

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consequences on the aquatic environment, human health, and crop growth *(22, 29)*. Further, chemicals such as chlorine have reduced efficacy in waters containing high levels of organic matter, which can commonly occur in surface waters. As sustainability is a key consideration in agricultural practices, more growers are seeking to reduce the use of chemicals in operations. UV-C light is increasingly recognized by the UV industry as an alternative to chemical sanitizers for agricultural surface water decontamination. However, there has been relatively little deployment of UV-C technologies by fresh produce growers.

UV-C is a popular technology for wastewater and drinking water decontamination because it is highly effective against human pathogens of high public health interest *(16, 33)* and is generally considered user-friendly. Unlike some chemical sanitizers *(39)*, there is also scarce evidence that UV-C may produce toxic by-products. UV-C is considered a physical decontamination method wherein microorganisms are inactivated following UV-C–induced photodamage to DNA. Without DNA repair mechanisms, the cell ceases to replicate, perform metabolic processes, or reproduce and eventually dies *(24, 28)*. Of the entire UV spectrum, wavelengths within the UV-C range (200 to 280 nm) are the most effective to inactivate microorganisms; hence, this range is denoted as the "germicidal range." Various studies report strategies for the successful implementation of UV-C to treat agricultural surface water in small-scale and large-scale operations *(1, 4, 30, 38)*. However, the low adoption of UV-C technologies indicates a large disconnect among the UV-C industry, academia, and fresh produce growers.

Produce grower adoption of UV-C technologies for preharvest and postharvest agricultural water decontamination purposes has not been thoroughly studied, though previous studies indicate it could be very low due to barriers such as low grower awareness of UV-C and low access to guidance on UV-C technologies. For example, Lamm et al. *(15)* reported that the majority (66.5%) of surveyed nursery and greenhouse growers in the United States did not perceive themselves as knowledgeable of chemical agricultural water treatment methods. Of note, those researchers chose to include UV light as a chemical, rather than a physical treatment method. Although the study's category "chemical agricultural water treatment methods" represented multiple decontamination strategies, it could be indicative of the knowledge level of nursery and greenhouse growers toward the use of UV-C technologies for agricultural water treatment. Raudales et al. *(27)* also identified an unmet need for more information on UV-C light tailored toward growers, such as the level of maintenance and supervision required during operation of UV-C technology. Moreover, there is sparse available literature regarding initial and ongoing costs of UV-C water decontamination systems. Because there is little information on actual produce grower adoption of UV-C for agricultural water decontamination, it is important to identify the factors affecting grower attitudes toward such technology. Addressing these limiting factors could, in turn, increase the likelihood of a grower adopting the technology.

The purpose of this study was to determine growers' level of knowledge, attitudes, and barriers to integrating UV-C technology for agricultural water decontamination in produce operations. Kansas and Missouri growers were selected for this study because these states have a rapidly growing specialty crop industry, and previous reports *(12, 40)* indicate that many growers in those states are in need of more information on agricultural water treatment strategies. The objectives of this study are (i) to identify agricultural water treatment practices of Kansas and Missouri produce growers; (ii) to evaluate growers' level of knowledge of UV-C for agricultural water decontamination; (iii) to determine produce growers' attitudes toward UV-C water treatment systems; and (iv) to determine growers' perceived barriers to investing in or integrating UV-C water treatment systems into growing operations.

MATERIALS AND METHODS

Conceptual framework of the study

The conceptual framework of this study is largely drawn from the technology acceptance model wherein the ease of use and grower and employee knowledge of the technology are major drivers affecting behavioral attitudes *(8, 9)*. Attitudes (rather than adoption) are emphasized in this study's framework because consultation with extension personnel in Kansas and Missouri indicated a low adoption rate of UV-C technologies among produce growers in these states. As such, demographic explanatory variables, including farm size, farm annual income from fresh produce sales, state, training certifications held, highest level of education, age, years of farming experience, and grower knowledge of UV-C, were used to explore internal and external factors affecting grower attitudes toward UV-C technology. Farm size (acreage) was found to positively impact the adoption of novel agricultural technologies such as precision agriculture due to the economy of scale *(26)*. In this study, physical size (acreage) and income are both included to represent urban agriculture operations that produce large quantities of horticultural crops in small spaces. State is included as a factor because grower attitudes may be influenced by the perceived profitability *(34)* due to different market sizes for fresh produce within Kansas and Missouri. Training certifications, education, age, and years of farming experience were included as possible explanatory variables indicating the likelihood of exposure to the basic concepts of UV-C light and its uses for agricultural water decontamination.

Grower attitudes toward UV-C for agricultural water treatment were further divided into perceived usefulness (PU), perceived ease of use, and perceived resource availability. Perceived usefulness and perceived ease of use are predefined in the technology acceptance model *(8)*, whereas perceived resource availability was added in accordance with relevant literature *(20)*. In this study, PU is the belief that the use of UV-C technology will eventually enhance the grower's agricultural water quality management. Perceived ease of use is the belief that the use of UV-C technology will require minimal management (physical and mental effort). Perceived resource availability is the belief the individual grower has access to the required resources (i.e., money, information) to use the technology. This factor was added to the framework because it was previously identified as highly influential to the adoption of novel agricultural technology *(3, 20)*.

Target population

The target population was defined as fresh produce growers in Kansas and Missouri. Because there is no publicly available complete registry of produce growers in either state, it was not possible to calculate the required number of responses based on population size and nonresponse rate. However, a target response rate of around 100 survey responses was followed, based on the methodology of similar survey studies in the region *(40)*.

Survey design

The survey instrument was developed by using the Qualtrics platform (Qualtrics, Provo, UT) for data collection and designed to measure produce growers' water quality management behavior, knowledge of and attitudes toward UV light technology, and assess the needs to be able to implement UV technology in their operations. A modified Delphi approach similar to that of Perry et al. *(25)* was used to develop the survey constructs. Briefly, five extension professionals and two other food safety experts were recruited to evaluate the preliminary survey questions for content and face validity. The survey was then pilot tested with produce growers ($n = 4$) from the target population. The survey instrument was amended by using the feedback from the growers and finalized after expert rereview. The Kansas State University Human Research Institutional Review Board approved the use of the survey.

Twenty questions were in the final survey *(Supplemental Material 1)*. The grower's current water management practices were assessed through six close-ended questions. The grower's level of knowledge of UV light and its applications was measured by using a series of five close-ended constructs with a 3-point scale (agree; don't know; and disagree). The grower's attitudes toward UV-based water decontamination systems for on-farm operations was evaluated by using eight constructs related to the measuring variable with a 5-point Likert scale (5–strongly agree; 4–mostly agree; 3–I don't know; 2–mostly disagree; 1–strongly disagree). The barriers to on-farm implementation of UV-C technology for agricultural water decontamination and the needs to overcome these barriers were assessed by using two close-ended, check-all-that-apply questions. Finally, the survey instrument collected demographic data regarding the grower's state of operation, gender, age, years of farming experience, highest level of education, farm and operation size, farm income, and current certifications. The possible options for the demographic information were determined according to the format of the U.S. Department of Agriculture Census (www.nass.usda.gov/AgCensus/). This format was selected based on grower familiarity with the census, in anticipation that this familiarity would prompt growers to be more likely to complete the demographic questions.

Survey distribution

The survey was available between February and October 2022 and administered to Kansas and Missouri growers in either an electronic- or paper-based format. Organizations with a significant proportion of the target population (i.e., specialty crop growers' groups, farmers' market associations) assisted in distributing the survey electronically through email LISTSERVs or in paper format at in-person events. To incentivize survey participation, growers could choose to be entered into a drawing to win 1 of 15 US$25 Visa gift cards. Of note, it was not possible to calculate the nonresponse rate as this study used a convenience sampling approach *(10)*. Convenience sampling (or "accidental" sampling) is a quick, inexpensive sampling method based on gathering responses from members of the target population who are conveniently available *(32)*. This method has been previously used to study the agricultural water treatment behaviors of growers in the region by sampling at events where growers are likely to be present (e.g., grower trainings, field days) *(40)*.

Data analysis

Similar to the methodology of Chen et al. *(5)*, the grower's knowledge of UV-C light and its applications were expressed as a knowledge index (KI), calculated as the sum of correct answers. If a grower agrees with a statement, it is treated as a correct answer and assigned 1 point each. Incorrect and "I don't know" responses received 0 points. The respondents' attitudes toward UV-C water treatment systems for on-farm operations were codified (where 5–strongly agree; 4–mostly agree; 3–I don't know; 2–mostly disagree; 1–strongly disagree). The sum of all the attitude constructs is hereafter referred to as the attitude score (AS). The AS was then divided into scores for perceived ease of use, PU, and perceived resource availability to test for factors that affect each aspect of the attitudes. To divide the AS, the perceived ease of use was calculated from the sum of scores for the first to third construct (they are easy to install; they are easy to maintain; they are easy to use), the PU from the sum of fourth, sixth, seventh, and eight construct (they are safe for humans to use; they can reduce the number of microorganisms in agricultural water; they can reduce the number of microorganisms on the surface of irrigated crops; they are suitable for treating agricultural waters in my operation), and the perceived resource availability from the score of the fifth construct (they are affordable). The constructs are a modified form of the constructs from the technology acceptance model survey instrument of Davis *(8)* and can also be referenced in *(Supplemental Material 1)*.

Ninety-one total responses to the survey were received; 82 of which were valid (from respondents currently growing fresh produce), and 66 were valid and complete. Descriptive analysis of the data was performed in Microsoft Excel (Microsoft Corporation, Redmond, WA), and statistical analysis was performed in SAS (Version 9.4, SAS Institute Inc., Cary, NC). Stepwise regression was applied to determine the factors affecting the total AS, perceived ease of use, PU, and perceived resource availability scores. Responses were not used for stepwise regression if the participants did not answer a significant portion of the demographic questions. Due to the relatively low number of valid, completed surveys received ($n = 66$), the demographics were restructured to facilitate analysis. Notably, the explanatory variables included the KI, state (STATE; Kansas, Missouri, or other), age (AGE; ≤54 or >54 years old), farming experience (FARM_EXP; ≤9 years or >9 years), education (EDUCATION; some high school, high school diploma, some college or master's degree, doctoral degree), farm size in acres (FARM_SIZE; <1 acre or ≥1 acre), farm income (FARM_INCOME; <US$1,000/year or ≥US$1,000/year), and training certifications held (good agricultural practices, Food Safety Modernization Act [FSMA], hazard analysis critical control point [HACCP], U.S. Department of Agriculture [USDA] organic, or other). For the check-all-that-apply constructs, participants could select multiple statements, leading to certain questions having results greater than the 81 valid responses.

RESULTS

Demographic characteristics of the respondents

There were 91 total responses received, 82 of which were valid (from respondents currently growing fresh produce). The demographics are shown in *Table 1*. Because participants could elect not to answer the question (i.e., selected prefer not to say), different questions may have a different number of responses.

Agricultural water treatment practices

The preharvest and postharvest agricultural water treatment practices of the surveyed growers are shown in *Figure 1*. For most growers responding to the survey, at least one of the water sources used for preharvest operations was a municipal water source (52 of 81, 64.2%). Ground water was the next most common source (29 of 81, 35.8%) followed by surface water (15 of 81, 18.5%). Growers were also using municipal (59 of 81, 72.8%), ground (19 of 81, 23.5%), and surface (5 of 81, 6.2%) water sources at a similar frequency for postharvest operations. Most of the water sources used for preharvest operations (84 of 96, 87.5%) and postharvest operations (63 of 83, 75.9%) were untreated. Growers treating preharvest agricultural water reported using chlorine-based sanitizers ($n = 4$), UV light ($n = 2$), organic acids ($n = 1$), or other treatments ($n = 5$). Growers treating postharvest agricultural water reported using chlorine-based sanitizers ($n = 6$), hydrogen peroxide ($n = 3$), organic acids ($n = 1$), UV light ($n = 1$), or other treatments ($n = 7$).

KI

Grower knowledge of UV-C light (KI) was measured using five close-ended constructs evaluated on a binary scale (where 1 = correct; 0 = incorrect). Accordingly, the maximum possible score for KI was 5, and the minimum possible score was 0. The mean KI was 2.61, with a standard deviation (SD) of 1.32 *(Table 2)*. Except for two questions, half or more of respondents indicated I don't know. The third construct was the most difficult, as participants most often provided an incorrect answer or selected I don't know. In contrast, the first and fifth construct appeared to be the least difficult and had the highest percentage of correct answers.

Grower attitudes toward UV-C for agricultural water decontamination

A total of 82 responses were received for the attitude and perceptions assessment portion of the survey. *Table 3* summarizes the results of asking growers to "please answer with the extent you agree or disagree with the following statements about UV light-based water treatment systems," by construct. Growers mostly answered I don't know to each of the survey constructs, and there were few who answered strongly disagree or mostly disagree to any of the constructs. Almost 33% (27 of 82) of the growers agreed to some extent that UV water treatment systems are easy to install, 39% (32 of 82) expressed some extent of agreement that the systems are easy to maintain, and 46.3% (38 of 82) agreed to various degrees that such systems were easy to operate.

Table 4 shows how the constructs translated into quantitative scores for overall attitudes, perceived ease of use, perceived resource availability, and PU of UV-C for agricultural water treatment according to the methodology previously described (see "Data analysis"). The mean total AS calculated from the sum of all the constructs was 29.02 (SD = 4.16) of a total possible score of 40; scores closer to 40 indicate a more positive view of UV-C technologies, whereas scores closer to 0 indicate more negative views. The mean score for perceived ease of use, calculated from the sum of the first, second, and third constructs, was 14.38 (SD = 2.29) of a possible score of 15.00. Scores closer to 15.00 indicate that UV-C technology was perceived as relatively easy to use, whereas scores closer to 0 indicate that the technology was perceived as more difficult to use. The mean score for perceived resource availability as indicated by the score of

TABLE 1. Demographic information of the survey participants

Survey construct	Response	% (*n*)
State the farm is located (*n* = 79)	Kansas	60.8 (48)
	Missouri	26.6 (21)
	Other	12.7 (10)
Age (*n* = 78)	Under 25	2.6 (2)
	25 to 34	16.7 (13)
	35 to 44	20.5 (16)
	45 to 54	12.8 (10)
	55 to 65	23.1 (18)
	65 to 74	20.5 (16)
	75 and older	3.8 (3)
Years of farming experience (*n* = 78)	Less than 4	34.6 (27)
	5 to 9	17.9 (14)
	10 to 14	14.1 (11)
	15 to 19	10.3 (8)
	20 to 24	3.8 (3)
	25 to 29	3.8 (3)
	30 yr and above	15.4 (12)
Highest level of education (*n* = 78)	High school diploma/General Educational Development	3.8 (3)
	Some college	20.5 (16)
	College/university degree	44.9 (35)
	Master's degree	24.4 (19)
	Doctoral degree	6.4 (5)
Farm size (*n* = 79)	<1 acre (<.40 ha)	39.2 (31)
	1 to 9 acres (0.40 to 3.64 ha)	43.0 (34)
	10 to 49 (4.05 to 19.83 ha)	11.4 (9)
	70 to 99 (28.33 to 40.06)	1.3 (1)
	100 to 139 (40.47 to 56.25 ha)	1.3 (1)
	140 to 179 (56.66 to 72.44 ha)	1.3 (1)
	500 or more (202.34 ha or more)	2.5 (2)
Annual farm income (*n* = 63)	Less than US$1,000	31.7 (20)
	US$1,000 to US$2,499	12.7 (8)
	US$2,500 to US$4,999	6.3 (4)
	US$5,000 to US$9,999	17.5 (11)
	US$10,000 to US$24,999	12.7 (8)
	US$25,000 to US$49,999	7.9 (5)
	US$50,000 to US$99,999	6.3 (4)
	US$100,000 to US$499,999	1.6 (1)
	US$500,000 or more	3.2 (2)

Continued on the next page.

TABLE 1. Demographic information of the survey participants (cont.)

Survey construct	Response	% (*n*)
Training certifications held (*n* = 80)	Good agricultural practices	15.0 (12)
	FSMA	42.5 (34)
	HACCP	1.2 (1)
	USDA organic	2.5 (2)
	Other	3.8 (3)
	None	45.0 (36)

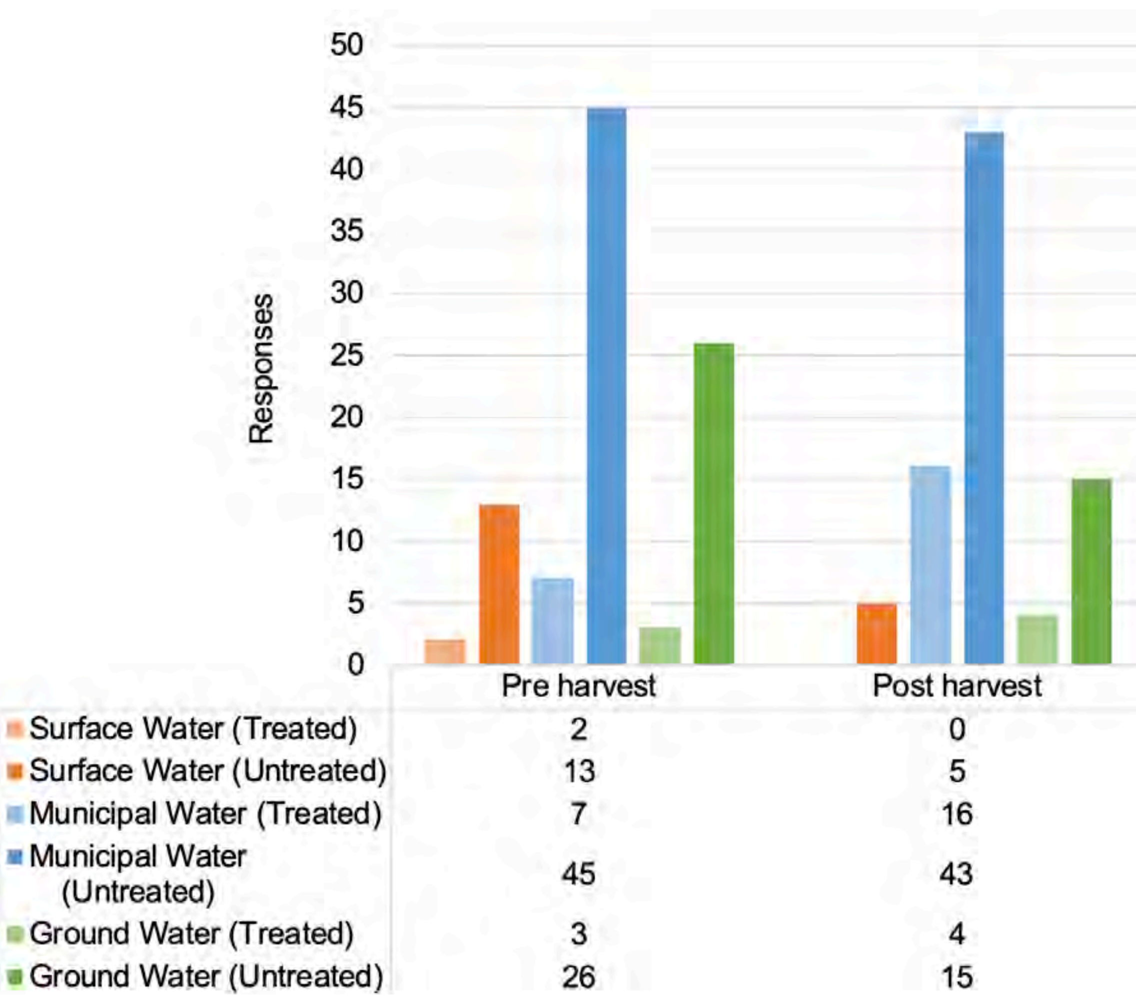

FIGURE 1. The source distribution for agricultural water sources used in preharvest and postharvest operations of surveyed fresh produce growers.

TABLE 2. The perceived barriers and needs of growers to facilitate the adoption of UV-C technology for agricultural water source treatment (n = 82)

Survey construct	Correct % (*n*)	Incorrect % (*n*)	I don't know % (*n*)
1. UV light can kill disease-causing germs	74.4 (61)	1.2 (1)	24.4 (20)
2. UV light is invisible to the naked eye	48.8 (40)	17.1 (14)	34.1 (28)
3. UV light cannot penetrate clothing	12.2 (10)	34.1 (28)	53.7 (44)
4. UV lamps have an infinite life span	53.7 (44)	3.6 (3)	42.7 (35)
5. UV light effectiveness depends on time and intensity	72.0 (59)	0.0 (0)	28.0 (23)

TABLE 3. Grower responses to constructs evaluating attitudes and perceptions toward UV-C for agricultural water treatment (n = 82)

Survey construct	Strongly disagree % (*n*)	Mostly disagree % (*n*)	I don't know % (*n*)	Mostly agree % (*n*)	Strongly agree % (*n*)
1. They are easy to install	0 (0)	1.2 (1)	65.9 (54)	25.6 (21)	7.3 (6)
2. They are easy to maintain	0 (0)	0 (0)	61.0 (50)	30.5 (25)	8.5 (7)
3. They are easy to use	0 (0)	1.2 (1)	52.4 (43)	34.1 (28)	12.2 (10)
4. They are safe for humans to use	0 (0)	2.4 (2)	36.6 (30)	35.4 (29)	25.6 (21)
5. They are affordable	1.2 (1)	13.4 (11)	69.5 (57)	13.4 (11)	2.4 (2)
6. They can reduce the number of microorganisms in agricultural water	0 (0)	0 (0)	30.5 (25)	31.7 (26)	37.8 (31)
7. They can reduce the number of microorganisms on the surface of irrigated crops	0 (0)	2.4 (2)	58.5 (48)	14.6 (12)	24.4 (20)
8. They are suitable for treating agricultural water(s) in my operation	1.2 (1)	3.6 (3)	59.8 (49)	19.5 (16)	15.8 (13)

TABLE 4. Grower overall attitudes, perceived ease of use, perceived resource availability, and PU of UV-C for agricultural water treatment (n = 82)[a]

Survey construct	Scoring constructs	Mean	SD	Score range
Overall attitudes	1 to 8	29.02	4.16	0 – 40
Perceived ease of use	1 to 3	14.38	2.29	0 – 15
Perceived resource availability	2	3.34	0.55	0 – 5
PU	4, 6 to 8	11.30	2.12	0 – 20

[a]Constructs indicates the survey constructs used to calculate each score *(Table 3)*.

TABLE 5. The perceived barriers and needs of growers to facilitate the adoption of UV-C technology for agricultural water source treatment (*n* = 81)

Survey construct		Responses % (*n*)
Barriers	Technical skills	30.9 (25)
	Cost	33.3 (27)
	Complicated	16.0 (13)
	Maintenance	11.1 (9)
	Not appropriate for my operation	34.6 (28)
	Other	29.6 (24)
Needs	Money	61.7 (50)
	Technical training	55.6 (45)
	Time	28.4 (23)
	More information about its benefits	63.0 (51)
	Other	9.9 (8)

the fifth construct was 3.34 (SD = 0.55) of a possible score of 5.00. Scores closer to 5 indicate that growers perceive the resources needed to implement UV-C technology (e.g., capital, guidance) as more available than scores closer to 0. The mean score for PU as calculated from the sum of the fourth, sixth, seventh, and eighth constructs was 11.30 (SD = 2.12) of a possible 15.00, with scores closer to 15.00 indicating that UV-C technology was perceived as useful to the grower's operation. The implications of these scores will be discussed in the following sections.

For the stepwise regression models, KI, state (STATE), grower age (AGE), years of farming experience (FARM_EXP), education (EDUCATION), farm size in acres (FARM_SIZE), annual farm income from fresh produce sales in U.S. dollars (FARM_INCOME), and trainings completed, or certificates held (TRAIN_CERT) were considered. The best fit (R^2 = 32.1%) to the AS data was achieved with a model incorporating KI ($P < 0.0001$), FARM_SIZE ($P = 0.0199$), FARM_INCOME ($P = 1.047$), and STATE ($P = 0.1237$). The best fit (R^2 = 19.2%) to the perceived ease of use scores was achieved with a model incorporating KI ($P < 0.0015$) and FARM_SIZE ($P = 0.0197$). The best fit (R^2 = 7.4%) to the perceived resource availability scores was achieved with a model incorporating KI ($P = 0.146$) and FARM_SIZE ($P = 0.032$). Finally, the best fit (R^2 = 33.5%) to the PU score was achieved with a model incorporating KI ($P < 0.0001$), FARM_INCOME ($P = 0.0368$), and STATE ($P = 0.0549$).

Grower barriers and resources needed to adopt UV-C technology

Table 5 shows the responses of growers to constructs assessing the barriers and needs of growers to facilitate the adoption UV-C for agricultural water decontamination. Note that because growers could select more than one response, the total number of responses may exceed the number of respondents (*n* = 81). Growers indicated that technical skills (30.9%) and cost (33.3%) were major barriers to UV-C adoption, whereas 34.6% reported that UV-C was not appropriate for their operations. Several growers (29.6%) indicated that there were "other" barriers preventing UV-C adoption, warranting further investigation. Growers (*n* = 81) generally perceived needing more information about the benefits of using UV-C (63.0%), money (61.7%), and technical training (55.6%) to overcome these barriers *(Table 5)*.

DISCUSSION

Agricultural water treatment trends among the surveyed growers

Zhao et al. *(40)* previously reported that many fresh produce growers in Kansas and Missouri were not testing the water according to the standards of the Produce Safety Rule (PSR) at the time. Most growers in this survey used municipal water for preharvest and postharvest activities, but 6.2% (5 of 81) of the growers used untreated surface water for postharvest activities; 18.5% (15 of 81) used untreated ground water for postharvest activities. The FSMA PSR requires that to use surface water postharvest, it must be treated. Thus, these results are potentially concerning, as a recent study found that many surface and ground water sources in the region may not be suitable for postharvest use without some sort of treatment *(12)*. Overall, these data could indicate there is still a critical need for grower education and engagement on proper agricultural water management practices. However, note that this study did not ask if the respondents were covered by the FSMA

PSR, which could potentially impact the decision to treat agricultural water, as growers not covered under PSR are not required to treat agricultural water and implement other mitigation strategies.

Interestingly, the reported water treatment practices from this study combined with other recent studies also indicate a potential niche for UV-C technologies. Although 64.2% (52 of 81) of growers in this study reported using municipal water in preharvest activities, McGehee and Raudales *(21)* recently reported that the residual chlorination of municipal water may be phytotoxic when used in a deep water culture hydroponic system, even if the chlorine levels meet industry standards. Other studies have also reported the phytotoxic effects (i.e., root damage, photosynthesis reduction) of residual chlorine following irrigation in greenhouse *(17)* and field conditions *(18)*. Accordingly, even though growers using municipal water are using a microbiologically safe water source, they could also be inadvertently decreasing crop productivity. In this study, 14.8% (12 of 81) of the growers reported using a mix of municipal water and either ground or surface water for preharvest use (data not shown). In the absence of events that would logistically restrict ground or surface water use (e.g., drought, aquifer depletion, or not having access to ground or surface water), these growers could potentially save money by using UV-C to treat these sources for preharvest activity (if there were concerns about the microbial quality of the water source) rather than paying for a municipal water supply. To perform a cost comparison between UV-C and municipal water, however, growers would need more information regarding the initial and ongoing costs of UV-C water decontamination systems, which is currently lacking in the literature.

Growers show mixed attitudes toward UV-C

The attitudes of produce growers in this study both conform and contradict with previous literature. Overall, growers had a more positive attitude toward the capacity of UV-C as an antimicrobial intervention for agricultural water (as indicated by the mean AS). When separated into perceived ease of use, PU, and perceived resource availability, growers had highly positive attitudes toward the perceived ease of use of UV-C technology. Of note, the perceived ease of use included constructs indicating the extent to which users agreed that UV light–based water treatment systems were easy to install, use, and maintain. This finding is in contradiction with Raudales et al. *(27)* that reported growers perceiving UV-C as one of the most difficult water treatment methods to monitor and maintain. However, this difference could be attributed to the different audience (northeast versus central United States), survey design, and sample sizes between the two studies.

Although the mean score for perceived resource availability (3.34 [SD = 0.55] of a possible score of 5) indicated a more positive attitude toward resource availability, it is also very close to a neutral score of 3. This score indicates that many growers either did not know or disagreed with the notion that they have access to the resources required to implement UV-C in operations (notably, capital). Not only is this finding consistent with the literature *(27)*, but it is also consistent with barriers later identified by the growers in this study. More than 50% of the growers reported needing more knowledge resources, monetary resources, and training resources to feel confident in the choice to implement UV-C in operations. Although addressing monetary concerns may be more difficult, the UV-C industry and academia have a vested interest in providing more opportunities to address the lack of technical training and guidance for growers on UV-C devices, though this point will be elaborated on in the following section.

Grower buy-in is a major factor in the deployment of UV-C in fresh produce operations *(11)* and may be highly impacted by understanding of the benefits of the technology to the current operation *(6, 31, 35, 36)*. Although growers had positive attitudes toward the usefulness of UV-C, they also identified the lack of information about its benefits as a barrier. The mean score for PU (11.30 [SD = 2.12] of a possible 15) indicated that many of the participants perceived UV-C water decontamination as useful to operations. This finding agrees with previous studies that show growers tend to believe that UV-C has some efficacy against plant pathogens and human pathogens *(27)*. However, this also could appear contradictory, as the barrier most identified by growers was also access to more information on the benefits of UV-C to operations. To clarify the information of most interest to growers, future studies in this domain should leverage open-ended questions or focus group discussions that would allow for more idea development than close-ended questions.

Growers need more technical guidance on UV-C

Previous studies on grower adoption of novel agricultural technologies suggests that growers must have confidence that the technology is effective *(2, 36)*. However, almost a quarter of the growers in this survey either did not know or disagreed with the KI construct that UV light can kill disease-causing germs, a statement that is well supported in the literature *(13, 23, 38)*. Moreover, 39% of the surveyed growers did not know that UV-C could not penetrate clothing, indicating that the human safety element of using UV-C is not widely known by growers. Although the constructs such as "UV light is invisible to the naked eye" and "UV lamps have an infinite life span" may not be consequential to how growers perceive UV-C, it could still be important to know for growers to safely operate UV-C devices. Once more, growers recognized the lack of technical guidance as a barrier to UV-C implementation. In fact, 55.6% of growers responded that they need more technical training before implementing UV-C in their operations. This point is reinforced by the contribution of grower knowledge of UV-C to the total and individual attitudes in the stepwise regression models for the AS, perceived ease of use, PU, and perceived resource availability.

More information is needed on factors impacting grower adoption of UV-C

Stepwise regression was able to identify which information collected in this study most impacted the attitudes and perceptions of growers toward UV-C. KI appeared in all four regression models, which could provide further evidence that knowledge of UV-C is critical in the grower decision-making process on whether to adopt UV-C for water treatment. However, understanding the effects of the other demographic factors warrants further study. For example, stepwise regression indicated that overall attitudes were affected by farm size, farm income, and state. Typically, the inclusion of farm size and farm income would not be surprising, as a previous study on the adoption of precision agriculture demonstrated that larger (in acreage) farms are more likely to invest in technologies that could be perceived as too costly for smaller operations *(14)*. However, growers in this survey largely did not know if UV-C devices for water treatment were affordable *(Table 3)*, which complicates the interpretation of two factors. More investigation on the effect of state is also justified, particularly to understand if the differences in perceived profitability (driven by market size) between Kansas and Missouri growers is indeed what is affecting overall attitudes and PU.

Study limitations

The low R^2 values of the stepwise regression also indicate that there are likely other variables impacting grower attitudes that were not measured in this study. The models had R^2 values between 7.5 to 33.5%, indicating there is still a large portion of the variation that is not accounted for. Future studies could measure growers' prior exposure to information about UV-C technologies by having growers self-evaluate knowledge (e.g., I perceive myself as extremely knowledgeable or extremely unknowledgeable on UV-C concepts) as in previous studies *(25, 27)*. Instead, in this study, factors such as age, experience, and education were used as surrogate predictors of grower knowledge of UV-C. To this point, there was no definitive information regarding if the respondents were covered (or not) by the FSMA PSR, which could potentially impact exposure to agricultural water treatment methods. Moreover, grower perceptions of the cost-effectiveness of UV-C could also be assessed, which was elaborated by Adrian et al. *(2)* as perceived net benefit. Survey respondents can also be asked about the crops they grow that could impact the investment they are willing to make in agricultural water treatment strategies. For instance, growers who produce commodities not commonly consumed raw (e.g., potatoes) may not have the same level of microbial risk as those who grow leafy greens that are more often consumed raw. Similarly, growers who do not apply irrigation to the edible portions of the produce during growing and growers who do not wash produce prior to sale (as is the case for strawberries) may also not feel this pressure. Finally, a potential limitation of this study (and suggestion for future studies) is that the word "treatment" was not defined in the survey. This definition is important to establish, as Zhao et al. *(40)* reported that some of the survey respondents considered methods such as sand-filtration to be agricultural water treatments. However, because they are not considered as such by the FSMA PSR, this could introduce inaccuracies during self-reporting of agricultural water management practices.

CONCLUSIONS

UV-C has been shown to be an effective, nonchemical technology for agricultural water treatment but has not been popularized in the fresh produce industry of the central United States. The present study indicates that the lack of grower adoption may be largely due to the absence of technical and general knowledge resources tailored toward growers. The level of grower knowledge of UV-C was shown to be a major predictor of grower attitudes toward UV-C for agricultural water treatment. Considering the identified barriers, growers held slightly positive attitudes toward UV-C and showed a degree of neutrality or uncertainty toward the extent that they perceived having sufficient resources to implement UV-C in their operations. More investigation is required to determine other significant factors, as the statistical models had a larger proportion of variation that was not accounted for. Clearly, more work is needed to provide resources and education to growers about the potential benefits of utilizing UV-C for water treatment for growing produce and other specialty crops.

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