PEER-REVIEWED ARTICLE

Food Protection Trends, Vol 41, No. 1, p. 56–69

2900 100th Street, Suite 309, Des Moines, IA 50322-3855

Gina Misra and Kristen E. Gibson*

Dept. of Food Science, Division of Agriculture, University of Arkansas, 2650 N. Young Ave., Fayetteville, AR 72704, USA

Characterization of Microgreen Growing Operations and Associated Food Safety Practices

ABSTRACT

Microgreen growing operations are an emerging industry. This study represents the first national survey of microgreen growers in the United States. An online survey, answered by 176 growers, included questions about farm demographics, growing techniques, microgreen varieties grown, and food safety practices. Microgreen growing operations that earned <10,000 USD/year in microgreen revenue (62%) producing microgreens in trays on stacked, artificially lit shelves (40.3%) dominated the response pool. Most farms surveyed opened after 2010 (75%). These farms primarily grow microgreens using peat (17.6%), coco coir (14.2%), or soil (15.3%). Sunflower (28%), peas (27%), and radish (29%) were the most popular microgreen varieties produced. Chi-square tests of association were performed to identify relationships between farm characteristics and food safety practices. Statistically significant relationships were found between growing media testing at least once per year and total number of employees (P = 0.015) and total number of employees who directly handle microgreens (P = 0.001), possibly indicating that larger operations are better equipped to engage in routine quality assurance procedures. Production system type (P = 0.001) and total number of employees (P = 0.011) were associated with pregermination seed disinfection; however, in this instance, smaller operations (i.e., average of four employees) reported seed disinfection more frequently than larger operations. Routine documentation practices were also significantly associated with annual microgreen revenue (P = 0.003), passing a good agricultural practices (GAP) audit (P = 0.001), and number of previous food safety trainings attended (P = 0.001). Overall, this study aims to inform research, outreach, and training efforts on the growing systems, microgreen varieties, and production practices relevant to microgreen safety.

INTRODUCTION

Farming systems that present alternatives to traditional field production of fresh produce are on the rise. Recent estimates for alternative farming systems are between 5 and 15% of total agricultural production in developing nations *(70)*. In developed countries such as the United

*Author for correspondence: Phone:+1 479.575.6844; Fax:+1 479.575.6936; E-mail address: keg005@uark.edu

States, the number of farmers' markets and community-supported agriculture organizations supplied by small urban producers—indicative of system type—has increased by more than 50% since the mid-2000s *(38)*. By 2014, approximately 800 million USD in indoor-grown food crops were sold in the United States *(56)*. This increase in popularity is often attributed to concurrent interests in preventing climate change impacts on farm productivity *(27, 37)*, access to fresh food for an increasingly urbanized population *(7, 46)*, and space travel research *(32, 69)*. Modern indoor farming was popularized as vertical farming *(21)* and has since evolved into a myriad of system types under the umbrella term of "controlled environment agriculture" (CEA).

Although there is a growing body of literature investigating the profitability and productivity of CEA *(24, 40, 48, 52, 55)*, less is known about food safety risks specific to these production systems or the crops typically grown within them. For example, microgreens—an emerging raw salad crop produced using CEA—are immature shoots of common vegetables harvested above the root at 10 to 20 days old *(33)*. Similar to leafy greens, microgreens can be produced outdoors, fully indoors, or in greenhouses as well as in hydroponic systems, in soil, or in soil-alternative-based systems *(33, 44, 63)*. And similar to sprouts, they are harvested at a young age after germinating in a warm, moist environment *(33, 68)*. These characteristics of microgreens make it a useful crop for studying the food safety of CEA-grown produce. Moreover, because microgreen production shares some similarities with sprouts and leafy greens, they may have similar food safety risks *(4, 8, 9, 30)*. Although there are no known outbreaks associated with microgreens, there have been multiple microgreen product recalls related to contamination with *Salmonella enterica* subsp. *enterica* and *Listeria monocytogenes* since 2016 in the United States *(60–62)* and Canada *(10–17)*. This recent trend underscores an urgent need to elucidate potential risk factors within microgreen growing operations that may render these products susceptible to contamination and possible foodborne pathogen transmission as the industry grows *(39)*.

Regulatory oversight for the safety of produce in the United States falls under the U.S. Food and Drug Administration's (FDA's) Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption, 21 CFR Part 112, commonly referred to as the Produce Safety Rule (PSR) *(57)*. The rule establishes best practices for the prevention of foodborne pathogen contamination of "covered produce," defined as produce that is typically eaten raw. The rule requires that growers meet certain standards for the use of biological soil amendments of animal origin, worker health and hygiene practices, irrigation water quality, equipment and surface sanitation practices, and the handling of wild and domesticated animals in the farm environment *(57)*. However, growers who earn <25,000 USD in annual produce sales (3-year average) are exempt from the rule, as is any produce grower who earns <500,000 USD (3-year average of all food sales) but half or more of whose covered produce sales are to qualified end users, including direct to consumers or food retail businesses within the same state or no more than 275 miles away *(57)*. Understanding the size and other characteristics of microgreen growing operations will determine (i) whether they tend to be exempt from the PSR and (ii) whether common industry practices exist that might be risk factors for human pathogen contamination of microgreens.

Furthermore, improved understanding of the farm food safety practices among CEA practitioners will assist training and outreach efforts targeting compliance challenges faced by these businesses. Whereas certain standards put forth by the PSR invariably apply to all fresh produce growers, such as hygiene and irrigation water quality, CEA growers may face challenges more similar to those faced by packing houses than conventional field growers *(57)*. There are no established guidelines for the production of microgreens at a commercial scale, although the PSR does recommend that microgreen growers voluntarily comply with the sprout recommendations *(57)*. However, sprout firms and microgreen operations have significantly different production practices *(44)*. Moreover, the FDA specifically states that microgreens are sprouts grown in soil or substrate but are not covered by subpart M of the PSR and, thus, are subject to other PSR requirements. Lastly, lab-based research directly examining food safety risks of common microgreen production systems should be informed by current industry trends and practices, which are largely unknown.

Although multiple surveys have been conducted to assess food safety practices on farms growing produce typically eaten raw *(1, 6, 18, 42)*, little is known about these practices within the emerging microgreen market. Two previous surveys of aquaponics facilities—a farming style resembling certain types of microgreen production—assessed only general production methods and demographics to determine the profitability and sustainability of this subset of CEA *(35, 36)*. Agrylist, a greenhouse management software company, has conducted one of the only annual, comprehensive surveys of the CEA industry for which data is freely available *(2, 3)*. However, this was a market research survey and does not focus on understanding grower compliance with food safety regulations. It also focuses on all types of produce grown in CEA farms, rather than just microgreen growing operations. Given these knowledge deficits, an online survey was designed and implemented for the purpose of understanding the demographics, farm characteristics, and food safety practices of microgreen growing operations selling their product in the United States.

MATERIALS AND METHODS

Ethics statement. The study was reviewed by the University of Arkansas Institutional Review Board (no. 1809144516), which determined it to be exempt. The survey contained a cover page with a description of the research objectives and a consent question that had to be answered before the participant could begin the survey. The survey did not collect personal identifying information such as farm name, participant name, street address, phone number, or e-mail address. However, the survey did collect the U.S. zip code for each farm to assess geographic distribution of farms surveyed and any regional differences in responses.

Survey development and implementation. Between 1 October 2018 and 30 March 2019, 142 complete responses were collected, along with an additional 34 incomplete responses (total = 176). Unless otherwise specified, all percentages reported were calculated with 176 as the denominator. Unanswered questions represent the response "no response" and are considered in the dataset. The survey was designed and distributed using the Qualtrics platform (Provo, UT). Participant inclusion criteria required that respondents sold microgreens to U.S. customers. Recruitment was conducted within online communities dedicated to microgreen growing and sales, hydroponic crop production, sustainability, and gardening, on social media sites Facebook and Reddit. Additional respondents were recruited through e-mail broadcasts on customer lists of a few popular seed and indoor farming supply companies. Lastly, approximately 80 e-mails were sent, with follow-up messages a week later, using the database LocalHarvest.org to search for all farms and community-supported agriculture programs in the United States that list "microgreens" as one of their available products. To incentivize completion, a discount coupon (e.g., 10% off, free shipping, etc.) was offered from the seed and supply businesses who distributed the survey link.

Survey questions. The survey question styles included 44 multiple-choice, 18 multiple-answer, 8 fill-in-the-blank, 1 ranking, 1 short answer, and 1 multiple-choice matrix. Not all questions were asked to all respondents; questions were shown to respondents based on answers given to previous questions. Questions were grouped by the following topics: farm demographics, product information, growing system, growing media, irrigation water, seed storage and handling, cleaning and worker hygiene, postharvest washing, postharvest storage, tracking and documentation, food safety training, and grower education. Following acceptance of the informed consent statement, growers were asked their country of origin and whether they sold microgreens to U.S. customers. If the respondent selected "no" to that question, they would be routed to an ending page telling them that the study being conducted is on microgreen growing operations with U.S. customers only, regardless of farm location. Completion time was estimated by the Qualtrics platform to be 15 min or less.

Validation of the survey instrument was performed both internally and externally by academic and industry professionals. Specifically, two types of validity were checked: content validity and face validity *(34)*. Question wording, appropriateness of questions, survey flow, and coverage of food safety topics were adjusted based on feedback from an expert in food safety education and outreach at Clemson University in the Department of Food, Nutrition, and Packaging Sciences. Significant attention was paid to minimizing the total number of questions, limiting matrix, fill-in-the-blank, and multiple-response questions, and the overall time required to complete the survey. Following expert judgment, three graduate students performed a pilot test of the survey and were provided with predetermined survey responses designed to guide them through specific pathways to test reliability. Finally, adjustments were made to the final instrument based on detailed discussions with two microgreen growers about their understanding of the questions in the survey. A sample of survey questions has been provided in *Table 1*

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Data analysis. Prior to data analysis, total microgreen production was standardized to pounds per month, even when respondents reported their total monthly production in trays, kilograms, or ounces. The conversion factor for the weight of microgreens produced per tray (0.46 lb per tray [10 by 20 in.]) was determined by using the average of typical yields per tray (10 by 20 in.) for seven microgreen varieties (sunflower, pea shoots, radish, kale, cabbage, amaranth, and basil).

Data from Qualtrics were exported and analyzed in Excel (Microsoft, Redmond, WA) and the R statistical platform (version 3.6.0) including the packages "descr" *(5)*, "maps" *(20)*, "ggplot2" *(64)*, and "data.table" *(23)*. Chi-square tests for independence were performed between categorical variables to determine whether statistically significant relationships exist between key food safety practices and farm characteristics where the answer type was multiple choice. For comparing numerical to categorical responses, Kruskal-Wallis tests were used. Kruskal-Wallis is a nonparametric analysis of variance that is more robust than ANOVA for nonnormally distributed datasets *(31)*. Because the data were skewed strongly toward smaller, beginning farms that grow microgreens in trays on stacked shelves and the sample sizes of the other groups were much smaller, improved accuracy of chi-square tests was attempted by adding a Monte Carlo simulated P-value to reduce risk of a type 1 error *(43)*. The P-values from multiple chi-square tests were also adjusted by the Bonferroni correction method to minimize accumulated error from running multiple chi-square tests.

For multiple-response questions, the large number of possible answer choices ($n = 122$), along with a large number of predictors relative to samples ($n = 143$), and nonnormally distributed data, necessitated the use of the R package "glmnet" *(25)*. This generalized linear modeling

TABLE 1. Example questions asked to respondents of the survey

Select topic areas	Sample questions
Farm demographics	How many total employees work at your farm?
	How many employees handle the microgreens?
	Each year, approximately how much (gross) revenue do you bring in from growing microgreens?
Product information	What varieties of microgreens do you produce (*Drag and drop your top five microgreens in order here*)
	Do you produce anything else besides microgreens?
Growing system/media	In which type of system do you produce half or more of your microgreens?
	What type of growth media do you use to produce half or more of your microgreens?
	Do you test your growth media for bacteria?
Irrigation water	How do you water your microgreens most of the time?
	What is the source of the water used on the microgreens?
	Do you treat your water? *(Examples: UV light, filtration, etc.)*
Cleaning and worker hygiene	Do workers who handle microgreens wash their hands while working?
	Do workers who handle microgreens use gloves?
	How frequently do you clean the following? *(tools, prep tables, floors)*
Postharvest practices	How do you harvest your microgreens? *(Check all that apply)*
	Where do you store your cut/picked microgreens?
	Do you wash your microgreens after harvesting?
Tracking and documentation	Do you routinely document any of the following practices? *(Check all that apply)*
	Do you use a lot numbering system?

approach with Lasso was used to determine whether linear relationships exist between key food safety practices and selected farm characteristics where multiple responses were given. A key benefit of using Lasso is prevention of overfitting of the data and selection of only the most relevant predictors for high-dimensional datasets.

RESULTS AND DISCUSSION

Demographics. The survey captured responses from microgreen growing operations across the United States *(Fig. 1)*. Fewer farms reported western U.S. zip codes; however, this regional response rate difference is consistent with a previous nationwide survey of produce farmers *(1)*. Farms also appeared to cluster around major metropolitan areas. According to Verlinden *(63)*, most microgreen growing operations are small and have approximately three to four employees—as confirmed by the present study—or are merely a part of larger diversified greenhouses or farms. In addition, microgreens may also be added as a crop during the "shoulder" season on small farms *(50)*.

Farm size was calculated by yearly revenue from microgreens, monthly microgreen production output, and number of employees. For revenue, respondents were asked "What is your yearly revenue from microgreens?" and were given the option to choose from five revenue categories or "Prefer not to respond." The number of farms for each revenue category is reported in *Table 2*. Eighteen farms preferred not to respond, and 34 farms did not choose any response. This nonresponse for revenue (29%) is similar to the national produce growers survey *(1)*; 25% of respondents to the national survey chose not to report revenue, so this nonresponse is likely not unique to microgreen growing operations.

Monthly production level was reported in trays (10 by 10 in. or 10 by 20 in.), pounds, ounces, kilograms, or "other." The values reported by respondents were then standardized to lb per month for comparison using the method described in "Data analysis." *Table 2* shows monthly production by farm revenue for those who elected to report income. The high standard deviations associated with these production estimates are likely due in some part to the error-prone method of standardizing lb per tray (see "Data analysis") and, to a lesser extent, due to respondents possibly erroneously entering their total farm production instead of just microgreen production and the differing sample sizes of each revenue category. It is estimated that microgreen

Revenue category (USD)	*n*	Avg microgreens produced (lb/month ± SD [kg/month ± SD])
<5,000	71	14.7 ± 18.9 (6.67 ± 8.57)
5,000–9,999	28	45.2 ± 59.4 (20.5 ± 26.9)
10,000–24,999	10	97.5 ± 144.4 (44.2 ± 65.5)
25,000–49,999	9	420.4 ± 1,043.4 (190.7 ± 473.3)
>50,000	6	7,629 ± 8,635 (3,460 ± 3,917)

TABLE 2. Monthly microgreen production by annual farm revenue

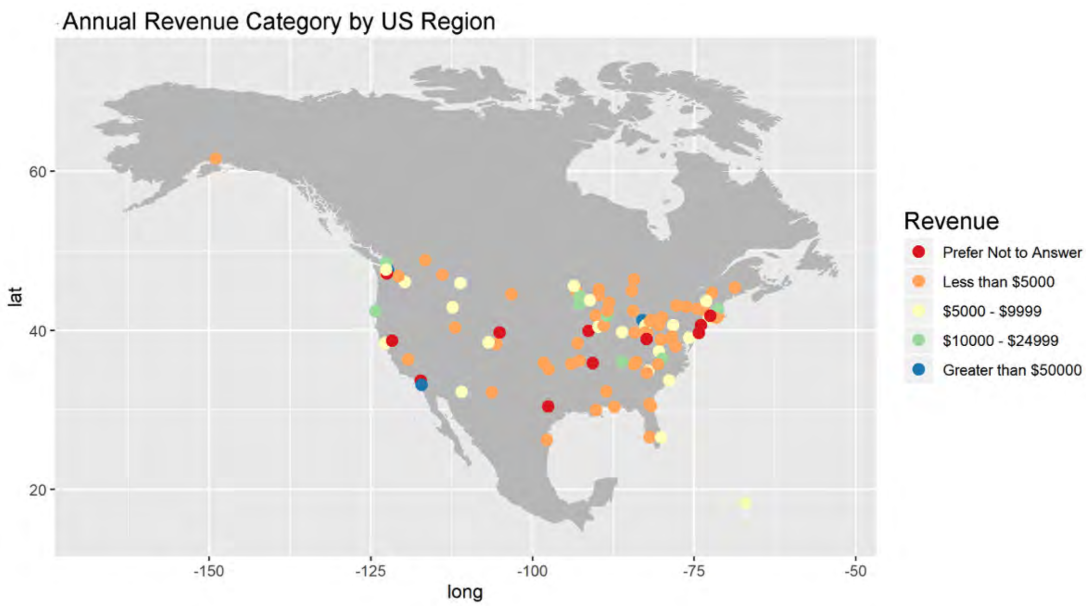

FIGURE 1. Annual revenue category by U.S. region. The nine farms in the 25,000 to 49,999 USD/year category are not shown because none of those farms provided a zip code.

yields can range from 0.3 to 3 kg/m^2 of growing space during a 10- to 14-day harvest period *(63)*. Based on this and the values reported in *Table 2*, those in the <5,000 USD revenue category could potentially operate in spaces ranging from 4.4 to 44 m^2, which is equivalent to the area of a midsized walk-in closet up to the size of an average studio apartment in the United States. For comparison, large commercial sprout firms in California growing "green" sprouts (i.e., radish, clover, and mixes similar to microgreen varieties) produce 318 to nearly 40,000 kg per week *(53)*.

For number of employees, farms in the <5,000 USD/year category had an average of 7 ± 9 employees ($n = 27$), and the 5,000 to 9,999 USD/year category had an average of 4 ± 2 employees ($n = 19$). The 10,000 to 24,999 USD/year category had an average of 6 ± 6 employees ($n = 7$). For larger farms, the 25,000 to 49,999 USD/year category had an average of 3 ± 1.5 employees ($n = 3$), and those earning greater than 50,000 USD/year had an average of 128 ± 171 employees ($n = 5$). Those farms who selected "prefer not to answer" had an average of 141 ± 316 employees ($n = 6$).

Growers' education level was primarily at the bachelor's level (23.9%) or "some college" (18.2%). "Some college" does not distinguish between participants who are still in college and those who never completed college. The third most common education level is an associate's degree, representing 9.7% of respondents. This rate is similar to the national average: 33.4% of U.S. citizens hold a bachelor's degree *(58)*.

Most microgreen growers (48.3%) reported having learned to grow microgreens using websites and online videos. The next most popular methods of learning to grow microgreens included "informally from other growers" (12.5%), "books and magazines" (9.1%), and "social media groups" (8%). However, high representation from internet learners is possibly due to the internet-intensive survey participant recruitment procedures.

The microgreen growers surveyed were mostly produce farmers, who were growing either only microgreens or microgreens along with other vegetable products. Livestock production at microgreen growing operations was less common. Among microgreen growers, 31% of farms produced other vegetable crops, 2% of farms produced livestock and animal products, 10% of farms produced both, and 24% of farms produced only microgreens. Thirty-two percent of respondents declined to answer the question. Of those growing other vegetable crops, 36.3% of respondents grew produce typically eaten raw and 25.5% grew produce rarely eaten raw. This may indicate that those operations growing other vegetable crops fall within the category of microgreens grown as part of larger greenhouse or farming operations *(63)*. The most common animal products included poultry (8%) and eggs (7.4%).

Most farms (74%) have opened in the past 10 years, and the majority of these fell into the "less than $5,000/year" revenue category. This suggests that most of these very small operations are beginner farmers. Interestingly, farms that opened after 2010 were more likely to be raising livestock or animal products (3.1%) or both animal and vegetable products (13.8%) compared to those farms that opened before 2010. Of the pre-2010 farms, 61.5% produced other vegetable crops, and 15% grew only microgreens. This suggests that, in addition to beginning growers, more experienced produce farmers are possibly adopting microgreen production. A 2019 webinar presented by the Sprout Safety Alliance and the International Sprout Growers Association also suggested that some of the possible food safety issues facing microgreen producers could be related to the influx in "new" producers without a history of produce farming *(50)*.

As stated previously, the PSR exempts farms earning <25,000 USD/year in revenue from covered produce, as well as farms earning <500,000 USD/year where at least half of all food sales are to a qualified end user *(57)*. However, respondents were only asked what their yearly revenue was for microgreens. The total revenue of farms that produced additional covered produce and other food items (i.e., livestock and other animal products) may exceed the exemption thresholds listed above, and, thus, some of these farms may not be exempt. However, even farms earning >50,000 USD/year in microgreen revenue, whether or not they sell other covered produce or other food products, may still primarily sell to a qualified end user, which would exempt them. Therefore, it is possible that nearly all respondents in this survey are exempt from the rule.

Growing techniques. The survey inquired about the system type and location where half or more of the respondent's microgreens are produced. System type is defined as the production system design, whether that is aquaponics, hydroponics, in ground, containers, raised beds, or trays on shelves. System location refers to the setting where the production takes place, whether that is fully indoors in a room with opaque walls, such as a storefront, warehouse, or residential building; in a greenhouse or hoop house with translucent or transparent walls; or completely outdoors. The most common combinations were an indoor residential space with trays on stacked shelves (26.7%), a container farm inside a climate-controlled greenhouse (8.5%), and an indoor commercial space with trays on stacked shelves (6.8%). These responses align well with what is reported in Table 2 with respect to microgreen production volume and the space required as discussed previously in "Demographics" *(63)*.

Farms earning >50,000 USD/year in microgreen revenue did not use trays on stacked shelves, whereas at least half of all other revenue categories did. The predominant production methods in the highest revenue category were unstacked container farms (50%) and hydroponic systems (16.7%). Hydroponic systems were less common among farms earning <25,000 USD/year. Of those growers who preferred not to disclose their yearly microgreen revenue, 17% used hydroponics and 39% used trays on stacked shelves, which possibly suggests that a mixture of both high- and low-earning farms were reluctant to give income information.

Most growers who responded to the survey utilized trays on stacked, artificially lit shelves, and they cultivated in a soil blend or soil substitute, particularly organic soil or peat blended with an aerator such as perlite and, occasionally, a biological soil amendment. The most common types of media used included peat moss (17.6%), organic soil (15.3%), and coco coir (14.2%). The most common additives included perlite (31%) and vermiculite (19.3%). Many growers did not report using any soil amendments (37%). However, the most common were worm castings (8.5%), green compost (6.2%), food compost (4.5%), and manure (2.3%). One grower used a unique fertilization mixture containing ingredients such as kelp meal, fossilized bat guano, and "aged forest products." Importantly, incoming soil mixes and ingredients were identified as potential food safety issues for microgreen producers by the Sprout Safety Alliance and International Sprout Growers Association *(49)*. The role of potentially contaminated soil-free cultivation matrices and the safety of microgreens has also been reviewed previously *(44)*; it has been specifically investigated *(22, 65, 66)* because this is a unique aspect of microgreen production that diverges from production of both sprouts and CEA-grown leafy greens.

Respondents were also asked how they disposed of their used growing media, and it was found that a single-use approach with growing media is common. Of growers, 43.8%

TABLE 3. Environmental conditions of most common microgreens system types

System location	Conditions[a]			n
	Water (°C)	Air (°C)	RH (%)	
Climate controlled greenhouse	18.1 ± 14	20.7 ± 16	65.8 ± 9.7	6
Indoors—commercial	18.9 ± 6.5	20.7 ± 4	60.0 ± 0	3
Indoors—residential	18.5 ± 9.5	22.3 ± 4.5	51.3 ± 12	24

[a]Conditions apply only to microgreen growers who answered all three questions ($n = 33$).

TABLE 4. Frequency of microgreen varieties produced

Variety[a]	%	n	Variety	%	n
Radish	29	42	Pea Tendrils	7	10
Sunflower	28	40	Cabbage	7	10
Pea Shoots	27	39	Mizuna	5	7
Arugula	18	26	Beet	5	7
Broccoli	16	23	Amaranth	5	7
Kale	15	21	Cilantro	4	6
Mustard	11	16	Nasturtium	3	5
Basil	9	13	Kohlrabi	3	5
Other	8	12	Popcorn	3	5
Daikon	8	12	Miscellaneous[b]	16	23

[a]Respondents ($n = 143$) were allowed to choose up to 5 from a list of 30 varieties, with a free response "other" category for writing in varieties not listed in the choices.

[b]The "miscellaneous" category in this table includes varieties grown by one to four farmers; these were collapsed for simplicity.

reported that they compost spent media after harvesting microgreens; 5.1% selected "We use it to grow other plants"; and 1.1% (two growers) reported that they reuse the media to grow more microgreens. It is unknown what the end use of the composted growing media is for the 43.8% of growers who produce it; thus, future investigations into this practice may be warranted.

Microgreens can be watered by either overhead spray irrigation or by subsurface irrigation. Bottom watering or drip irrigation, where the water does not touch the microgreens, was reported by 33% of respondents. Overhead watering, where the water does touch the edible portion of the microgreens, was reported by 23.9% of respondents. This question was left blank by the other 42.6% of respondents. Previous microgreen food safety studies comparing the risks of overhead versus subsurface irrigation are limited, although it has been studied in other leafy greens *(45)*. Neither of the previous studies that investigated watering technique in microgreens production *(28, 68)* found statistically significant differences in the transfer of *Escherichia coli* O157:H7 to microgreens between the two watering methods. However, a difference in *E. coli* O157:H7 transfer to full-sized lettuce was found by Solomon et al. *(47)*. More specifically, lettuce was nearly five times more likely to be contaminated with *E. coli* O157:H7 following overhead irrigation compared to subsurface irrigation, although there was still a risk of contamination related to subsurface irrigation. A systematic review of risk factors for preharvest microbial contamination of fruits and vegetables also confirmed that overhead, spray irrigation with contaminated water was an important risk factor to target for control and prevention of produce contamination *(41)*.

Approximately half of all farms (51.1%) reported monitoring environmental conditions of their growing space. The average ambient temperature, water temperature, and relative humidity for each production environment type are shown in *Table 3*. Nonresponses were excluded from this analysis (69 of 176). The 33 respondents who reported all three variables were used for this comparison. The average relative humidity in microgreen production systems surveyed here ranged from 50 to 65%. By contrast, relative humidity in sprouted seed production environments tends to be closer to 70% *(68)*, which likely aids microbial proliferation when pathogens are present. This may indicate a possible difference in food safety risk between microgreens and sprouted seeds. Studies on other types of covered produce *(51, 54)* indicate the possibility that low relative humidity is generally linked to pathogen inactivation, although it ultimately depends on pathogen and produce type.

Agricultural water. The most common sources of irrigation water include municipal water (32.4%) and well water (29.5%). Rainwater collection (2.8%), surface water (1.1%), and gray water (0.6%, only one farm) were also used. The majority of farms did not impose any user-side water treatment beyond what may be performed at the source, such as at a municipal water treatment plant. Activated charcoal, reverse osmosis, and sediment filtration were the most commonly used methods among the few respondents who treated their water. Further discussion of water testing and treatment can be found in the section "Multiple linear regression of food safety practices."

Microgreen varieties. Sunflower, pea shoots, and radish were the top three most commonly grown microgreens *(Table 4)*. These microgreens may be preferred because several factors make them the most profitable: their ease of cultivation and short seed-to-harvest period, the low cost of seeds relative to other varieties, and the high fresh weight yield per unit of tray area. Thus, it is critical that microgreen food safety research focus on these varieties. So far, no research has been published that investigates the food safety risk of sunflower and pea shoots, although radish microgreens were investigated in three studies *(65, 66, 68)*.

Key food safety practices. Chi-square tests of association were performed to identify statistically significant relationships between farm characteristics and food safety practices that are relevant to the PSR. Farm characteristics tested included farm size by revenue, farm size by number of employees, number of employees directly handling microgreens, whether or not the farm has passed a good agricultural practices (GAP) audit, number of previous food safety trainings taken, last completed education level, type of production system, and monthly microgreen production in pounds. These characteristics were tested against the following practices: documentation, water testing, seed disinfection, hand washing, postharvest washing, grow media testing, and cleaning frequencies. *Table 5* summarizes these relationships. The values for n varied across each comparison because the statistical tests required exclusion of "NA" values. Sample sizes for each comparison are cited within the text.

Several questions inquired about microbiological testing of growing media. Participants (n = 104) were asked "Do you test your soil or growing media for bacteria?"; responses included "yes" (11.5%), "no" (87.5%), and "I don't know" (1%). Testing frequency was reported as follows: twice a

TABLE 5. Summary of significant relationships found using Pearson's chi-square tests[a]

Correlates	D	WT	SD	HW	PW	GT	S
Farm size by revenue category	0.003[b]	0.073	0.745	0.341	0.971	0.291	0.942
No. of total employees	0.503	0.631	0.011[b]	0.158	0.873	0.015[b]	0.688
No. of employees handling microgreens	0.149	0.454	0.106	0.100	0.409	0.001[c]	0.126
Passed a GAP audit	0.001[c]	0.211	0.470	1.000	0.430	0.634	0.209
No. of previous food safety trainings	0.001[c]	0.201	0.823	0.613	0.662	0.123	0.790
Last completed education level	0.809	0.374	0.710	0.138	0.396	0.925	0.346
Growing system type	0.065	0.010[b]	0.001[c]	0.151	0.630	0.321	0.499
Production (lb/month)	0.321	0.598	0.646	0.245	0.539	0.334	0.182

[a]Rows, farm characteristics; columns, food safety practices. D, documentation; WT, water testing; SD, seed disinfection; HW, hand washing; PW, postharvest washing; GT, growing media testing; S, daily cleaning of surfaces.

[b]Relationships no longer significant after Bonferroni correction.

[c]Statistically significant relationships after Bonferroni correction ($P < 0.05$).

year (2%), four times per year (4%), and more than four times per year (2%). In addition, 4% of growers tested their growing media but did not know how often, and one grower (1%) did not know whether their farm's growing media was tested specifically for bacteria. Statistically significant relationships were found between growing media testing at least once per year and both the total number of employees ($P = 0.015$) and the total number of employees who directly handle the microgreens ($P = 0.001$). This may indicate that larger microgreen operations are better equipped to engage in routine quality assurance procedures such as microbiological testing of media. Although the PSR does not explicitly require microbiological soil testing, the importance of environmental monitoring of food contact surfaces *(29)* and data on differential survival of common foodborne pathogens on soil-free growing media types *(22, 65)* indicate that the growing media is not without risk. Testing of growing media is not only uncommon among microgreen growers, but it appears not to be influenced by any farm characteristics tested. Soil testing may not be included in requirements for passing a GAP audit or included in farm food safety trainings because it is not explicitly required under the PSR. Furthermore, the only discussion of growing media in the PSR is related to the proper use of biological soil amendments of animal origin *(57)*. Biological soil amendments are used infrequently among microgreen producers; among the small number who use them, worm castings were mentioned most often. By contrast, two surveys of field-grown produce farmers *(1, 6)* indicated that manure use is quite common.

For questions about irrigation water testing, the only farm characteristic that had a statistically significant relationship with irrigation water testing at least once per year was the type of production system ($P = 0.01$). The source of irrigation water (e.g., municipal, groundwater, surface water, rainwater, etc.) was hypothesized to be an influencing factor but was not significant in our data ($P = 0.49$) because most operations used either groundwater or a municipal water source. Linear regression showed that "collected rainwater" was a negative predictor of water testing (see Supplemental *Table S2*). Overall, 48% of growers who responded to the question test their irrigation water source at least once per year. This proportion of growers who implement water testing is similar to that reported in a 2018 national survey of produce growers *(1)*. Of those who answered the question ($n = 114$), all aquaponics ($n = 2$) and hydroponics ($n = 5$) practitioners in the survey reported testing their water more than once per year. For growers who used the stacked tray method, 18 tested their water once per year, 8 tested more than once per year, and 5 did not perform water testing. Among unstacked container growers, 6 tested once per year, 3 tested more than once per year, and 3 did not perform any testing. Because the majority of responses for agricultural water sources were either municipal or well water (61.9%), the reported testing frequencies are in line with requirements under the PSR *(57)*.

For water treatment, 46.6% of respondents ($n = 176$) did not perform user-side water treatment, and 35% did not answer the question. The most popular type of water treatment method among those who did treat their water included activated charcoal filtration (6.2%), a sediment filter (6.2%), and reverse osmosis (5.1%). Respondents were allowed to choose more than one response for this question. There were many unique combinations of water treatments reported by respondents, but the most common combination of water treatment methods was a sediment filter along with an activated charcoal filter ($n = 5$).

Seed disinfection was also examined. Statistically significant relationships existed between pregermination seed disinfection and two farm characteristics: production system type ($P = 0.001$) and total number of employees ($P = 0.011$). Interestingly, those farms that did not disinfect their seeds prior to germination had an average of 29 total employees, whereas farms that did disinfect their seeds averaged 4 total employees. An in-depth survey of 19 food safety experts and 32 produce growers *(42)* also challenges the assumption that larger farms are more likely to engage in more food safety practices than smaller farms. The authors found that if a recommended food safety practice is more challenging to implement on a larger scale, large farms are less likely to do it. Seed disinfection may be a practice that is difficult to scale. However, seed treatment for reduction of microorganisms of public health significance is a requirement for sprout producers, distributors, or suppliers under subpart M of the PSR—an important distinction between microgreens and sprouts *(57)*.

By production system type, 40 stacked-tray growers ($n = 71$) disinfected their seeds, 28 did not, and 2 did not respond. For all other production system types combined ($n = 47$), a greater proportion of growers did not disinfect their seeds compared to those who did. In particular, 17 of 22 container farms reported not disinfecting seeds. This may be indicative of the perception of less risk associated with growing microgreens as compared to sprouts, which have the requirement for seed treatment. Among growers of all system types who reported having a seed disinfection step ($n = 46$), 42 (91%) used a hydrogen peroxide soak. Sodium hypochlorite ($n = 3$) and vinegar ($n = 1$) were also reported. However, it is unknown whether the reported methods for disinfection are based on scientifically valid methods because concentration and contact time were not asked.

Harvest-related practices surveyed included harvest method, postharvest washing, and presale storage. Postharvest washing was performed by 34 farms (19.3%) and was not performed by 77 farms (43.8%), whereas 65 farms (36.9%) did not respond to the question. The lack of postharvest washing aligns with peer-reviewed research that reports a negative effect on shelf life as indicated by final microbial counts and damage to plant tissues, especially for the more delicate microgreen varieties (e.g., kale, broccoli, cilantro) *(63, 67)*. Meanwhile, postharvest washing is an industry-wide practice for both sprouts and fresh-cut leafy greens *(19, 59)*. The most common microgreen varieties washed after harvest were "all varieties" (20 farms, 11.4%), "sunflower" (10 farms, 5.7%), and "radish" (4 farms, 2%). There were no significant relationships found between postharvest washing of microgreens and any of the farm characteristics tested. The most common microgreen harvest method is to hand cut with scissors or a knife—a technique used by 56% of respondents. An additional 21% (n = 32) sold their microgreens as a "living tray." A living tray refers to the sale of the microgreens live and unharvested, in their original growing container. Hand picking and other methods of harvesting were uncommon, and 37% of participants did not answer the harvest technique question. The most common postharvest storage method was in a refrigerator or cooler (52%), whereas 3% of growers stored their microgreens at room temperature, and the remaining growers did not respond to this question. The average refrigerated storage time from harvest to sale for cut microgreens was 14.6 ± 14.1 h (n = 92), and the average room temperature storage time was 36.8 ± 37 h (n = 5). For living tray storage, the average cooler time was 20.7 ± 17.4 h (n = 7), and room temperature storage was 18 ± 25 h (n = 25). Thus, room temperature storage is more common among growers who sell living trays. When compared with similar crops, such as baby lettuces and sprouts, there are distinct differences in postharvest storage practices. Specifically, sprouts should be rapidly cooled to 0°C (32°F) to achieve maximum storage potential of 5 to 9 days, and storage at 10°C (50°F) or above—as reported here for microgreens—would limit the shelf life to < 2 days due to high respiration rates *(19)*. Meanwhile, leafy greens can be stored up to 14 days in temperatures ranging from 0 to 10°C (32 to 50°F) following rapid cooling and postharvest processing when applicable *(26)*. Depending on the variety, microgreens can be stored from 7 days to 3 weeks under refrigerated conditions. Nevertheless, it is concerning that microgreen growers who store cut microgreens at room temperature do so for a longer period of time on average than those who use a cooler and that storage times among growers suffer from high variability.

Regarding cleaning practices, respondents were asked how often they cleaned various food and non-food contact surfaces such as tools, growing trays, preparation tables, and floors (n = 143). Daily cleaning of at least one of these surfaces was common among respondents (64%). Equipment cleaning is broken down by surface type and frequency in *Figure 2*. There were no statistically significant relationships between daily cleaning of at least one surface and any of the farm characteristics tested. Because we specifically asked about cleaning frequency, it is unknown whether the respondents also sanitized surfaces within their operations. A 2019 webinar on controlling *Listeria* within sprout or microgreen growing operations specifically addresses the need for environmental monitoring plans and effective sanitation plans per subpart M of the PSR. Meanwhile, subpart L of the PSR—which

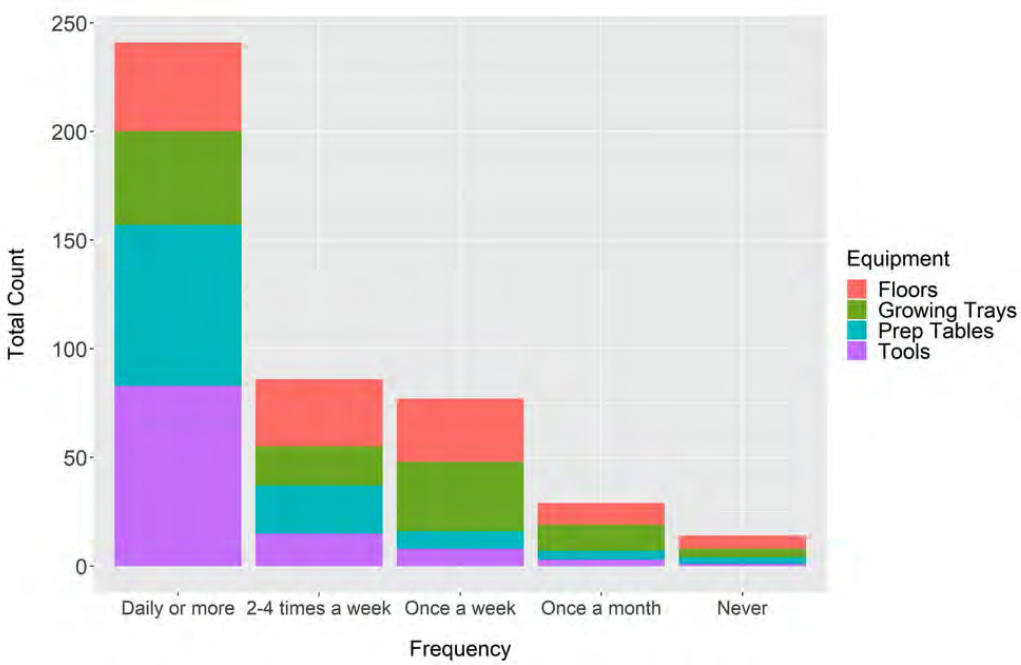

FIGURE 2. Frequency of equipment cleaning for floors, preparation tables, growing trays, and tools for planting and harvesting (n = 111).

addresses equipment, tools, buildings, and sanitation related to all other covered produce—requires all food contact surfaces to be cleaned, but only sanitized when "necessary and appropriate" *(49, 57)*.

For worker hygiene practices, respondents were asked about worker hand washing during production ($n = 112$). The practice is common, with 95.5% of respondents reporting "yes" to the question "Do workers routinely wash their hands during microgreen production?" When asked at which specific production steps workers routinely washed their hands, 32% reported washing before handling seeds, before harvesting, and before packaging. Another 20% of farms reported washing at those steps as well as before watering microgreens. An additional 17% of farms reported washing at all steps as well as at random times throughout the day. There was a statistically significant relationship between hand washing and disposable glove use ($P = 0.025$): growers who washed hands routinely were more likely to also use disposable gloves. However, no other farm characteristics tested were found to be related to hand washing. Disposable glove use among farms was 32.4%, and the steps at which disposable gloves were most commonly used included during harvest (27.4%) and packaging (26.7%). An additional 16% of respondents reported using gloves while handling seeds. Overall, the hand hygiene practices reported here for microgreen growing operations align with those prescribed by subpart M of the PSR for the production and handling of sprouts *(57)*.

For record-keeping practices, respondents were asked to report which farm processes they routinely documented and were allowed to give more than one answer. Using this input, the number of farm processes documented was counted, and the assumption was made that a greater number of farm processes documented implies a greater degree of documentation compliance. "No routine documentation" was assigned a score of "0." Statistically significant relationships were found between number of farm processes documented (zero to eight processes) and annual microgreen revenue ($P = 0.003$), passing a GAP audit ($P = 0.001$), and number of previous food safety trainings attended ($P = 0.001$). A greater proportion of farms earning >25,000 USD/year had higher documentation numbers compared to farms earning less than the PSR exemption cutoff. The observed relationship between annual microgreen revenue and documentation is consistent with findings from a previous produce grower survey *(1)* that showed that written documentation was more prevalent among larger, commercial-sized farms. Additionally, it appears that passing a GAP audit or attending food safety training influences the number of processes documented. A greater proportion of farms with high documentation numbers (five to eight processes) had previously passed a GAP audit, whereas only one farm that passed a GAP audit had a documentation number of "1." Conversely, the majority of farms that had not pursued or passed a GAP audit documented four processes or fewer. Overall, the most common processes documented ($n = 176$) include standard operating procedures (26%), water testing (24.4%), cleaning (23.3%), employee food safety training (22.7%), shipping and receiving (20.4%), growth media testing (11.4%), and recalls (8.5%). Furthermore, 22.7% of respondents reported "no routine documentation." Given that some level of record keeping is required for each subpart of the PSR, this is a key food safety practice within microgreen growing operations that should be addressed.

Multiple linear regression of food safety practices. The same seven key food safety practices (documentation, water testing frequency, seed disinfection, routine hand washing, postharvest washing of microgreens, growing media testing frequency, and daily surface cleaning) analyzed by chi-square tests were also tested by linear regression, using *glmnet* with Lasso ($\alpha = 1$, using cross-validation to obtain λ_{min}), against predictors collected from multiple-answer questions (certification type, food safety training type, method of learning to grow microgreens, production of other farm products aside from microgreens, growing media type, microgreen variety grown, irrigation water source, and water treatment method). See "Data analysis" section under "Materials and Methods" for rationale behind not comparing these responses with chi-square tests.

Variation in documentation level (adjusted $R^2 = 0.55$) could be negatively predicted by not having any certifications (such as GAP, third-party sustainability, or certified organic) and by irrigating with water that had no user-side treatment (regardless of source). Positive predictors of variation in documentation include passing a GAP audit, a food safety lecture at work, Global Food Safety Initiative training, and having a county-level food safety certification *(Table 1)*. If genuine, the moderate statistical relationship between documentation and greater farm revenue, greater numbers of food safety trainings attended, and passing a food safety audit may suggest that increasing the rate of food safety training of very small microgreen operations may increase documentation practices. A previous survey found a relationship between revenue and documentation *(1)* similar to that in the present study. More specifically, the study authors reported that nearly 20% of their total respondents ($n = 311$) kept no records, and those were primarily farms with reported revenues of <250,000 USD. In addition, when very small growers did report keeping written records, the prevalence was half that of commercial-size growers *(1)*. It may be that larger farms have a greater need for documentation or that they have more resources to implement it. It is worth considering, however, that many microgreen farms may not prioritize routine documentation due to being exempt from the PSR.

Variation in water testing frequency could be predicted (adjusted $R^2 = 0.62$) by multiple categories each for food safety training type, method of learning to grow microgreens, other farm products produced, growing media type, microgreen variety grown, irrigation water source, and water treatment method. See *Table 2* for individual categories and their coefficients and *P*-values. Notably, the Produce Safety Alliance Grower training and the Global Food Safety Initiative training were positive predictors of variation in water testing treatment. This could indicate that growers who are more conscientious about food safety issues in general both engage in regular water testing and attend food safety trainings, or that food safety trainings are at least somewhat effective in encouraging farmers to test their irrigation water. Water testing becomes an even more important educational objective when taking into account that the majority of microgreen growers surveyed do not implement any user-side water treatment (or did not respond to the question), such as reverse osmosis, UV light, or other filtration method. Meanwhile, some variables were unexpected predictors of water testing frequency, such as use of green compost or organic soil and being a self-taught grower, and, thus, the relationship may be an artifact of collinearity between predictor variables.

Survey limitations. The survey respondents were predominantly very small farms, earning less than 10,000 USD in annual microgreen revenue. This is likely due to the utilization of online microgreen growing communities as the primary recruitment strategy, which may be biased toward small-scale and beginning growers. However, when commercial-scale farms were successfully reached using direct e-mails, they were often reluctant to answer the majority of the survey questions. Two farms directly expressed concern about the sharing of trade secrets with potential competitors. Furthermore, because it is an emerging industry, these data may be reflective of a true greater proportion of beginning growers to large-scale commercial operations, as was also identified during the 2019 Sprout Safety Alliance–International Sprout Growers Association webinar on controlling *Listeria* (*50*). Nevertheless, confidence in the statistical relationships demonstrated, particularly with the linear regression, is moderate to low. This is because categories did not have equal values of *n*; data were not normally distributed; and overall sample sizes in each category were low except for those favoring small, beginning farms growing microgreens in trays on stacked shelves. Therefore, future surveys should aim for a larger sample size and targeted recruitment of commercial-scale, non-exempt microgreen farms.

CONCLUSIONS

This is the first survey of the U.S. microgreens industry that characterizes the business operations as well as relevant food safety practices. Based on the survey results, recommendations for future training and outreach efforts include greater consideration for the impact of soil-free growing media on food safety risk and the importance of routine documentation of farm procedures, irrigation water testing, and proper storage of microgreens prior to sale. Future research should consider the most commonly grown varieties of microgreens, differential risk among soil-free growing matrices and production system types, and the utility of applying similar seed disinfection practices to microgreen production presently used for sprouted seeds. Environmental monitoring best practices for microgreen growers may also be needed if the commercial popularity of CEA-farmed produce continues to increase.

ACKNOWLEDGMENTS

This work was supported in part by the National Institute of Food and Agriculture (NIFA), U.S. Department of Agriculture (USDA), Hatch Act funding, and the University of Arkansas Doctoral Academy Fellowship for 2017 to 2019. We also acknowledge Dr. Jyotishka Datta for assistance with the statistical methods, Dr. Angela Fraser for expert survey evaluation, and Ozark All Seasons and GreenSpace for nonscientific survey evaluation.

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