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ORIGINAL ARTICLE

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The effect of aquaponics on tomato (*Solanum lycopersicum*) sensory, quality, and safety outcomes

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Abstract: Resource-efficient food production practices are needed to support a sustainable food system. Aquaponics, a system where fish and produce are grown symbiotically in the same water circulating system, minimizes water usage, fertilizer input, and waste production. However, the impact of aquaponics on produce quality is underexplored. We utilize objective testing, descriptive analysis, and consumer acceptance to characterize the impact of aquaponics on tomato quality. Two tomato varieties were grown in an aquaponics system and compared with soil-grown controls across 3 years. Safety was assessed by analyzing coliforms and confirming the absence of *Escherichia coli*. Weight, texture, color, moisture, titratable acidity, brix, and phenolic and antioxidant measurements were assessed. A semitrained descriptive sensory panel assessed 13 tomato attributes and acceptance was determined using untrained participants. Aquaponic tomatoes were frequently lighter and yellower in color and lower in brix. Descriptive analysis indicated significant differences in several sensory attributes, though these findings were inconsistent between years and varieties. Nutrient deficiencies may explain quality differences, as iron supplementation improved outcomes. Notably, the objective and descriptive differences minimally impacted consumer acceptance, as we found no significant differences in taste, texture, or appearance liking between production method in either variety. Despite variation in produce quality across years, aquaponics tomatoes pose minimal *E. coli* risk and are liked as much as soil-grown tomatoes. These findings demonstrate that aquaponics can produce products that are as acceptable as their soil-grown counterparts.

KEYWORDS
controlled environment agriculture, sustainability

Brittany Kralik and Natalie Nieschwitz contributed equally to this work.

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Practical Application: Aquaponic tomatoes are as safe as soil-grown tomatoes. Furthermore, aquaponics tomatoes are liked as much as soil-grown tomatoes. Careful monitoring of nutrients in an aquaponic system may optimize quality. Overall, aquaponics has a minimal impact on tomato quality and thus is a sustainable food production method that can compete with conventional products on quality.

1 | INTRODUCTION

Global food production, which relies primarily on open field agriculture, is responsible for the majority of arable land and water use and is the largest contributor to eutrophication; furthermore, many agricultural practices threaten biodiversity and both terrestrial and aquatic habitats (Poore & Nemecek, 2018). Controlled environment agricultural (CEA) techniques, such as vertical farming and hydroponics, are evolving in response to the land, water, and resource use concerns associated with open-field food agriculture practices.

Aquaponics, the integration of aquaculture and hydroponics, is a CEA practice that addresses the limitations of both aquaculture and agriculture. Although several configurations are possible in aquaponics, the basic principles include the circulation of nitrogen in fish waste (following conversion from ammonia to nitrates by nitrifying bacteria) to plants as a source of nutrients; the plants then remove the nitrogen and other nutrients before the water is circulated back to the fish (Goddek et al., 2015; Klinger & Naylor, 2012). Most systems require only fish feed and energy as inputs (Chen et al., 2020). By recirculating water and nutrients and upcycling fish waste and uneaten feed, aquaponics offers many advantages over traditional aquaculture and agriculture, such as requiring less water (90%–98% less), land, and fertilizer, and minimizing waste (Al-Hafedh et al., 2008; Chen et al., 2020; Klinger & Naylor, 2012; Suhl et al., 2016). Due to these benefits, aquaponics is considered a viable option for food production in marginal or urban areas (reviewed in Dos Santos, 2016; Greenfeld, Becker, McIlwain, et al., 2019). Furthermore, because multiple products are produced with relatively few inputs, aquaponics is more resource efficient than hydroponics, thus minimizing environmental impacts on a per-product basis (Armenta-Bojórquez et al., 2021; Chen et al., 2020; Love et al., 2015; Suhl et al., 2016).

Despite aquaponics' potential environmental advantages, several limitations have impeded its widespread growth and acceptance. While concerns regarding its profitability (Greenfeld, Becker, McIlwain, et al., 2019; Love et al., 2015), complexity (Suhl et al., 2016), and productivity (Yang & Kim, 2020) have been explored previously, questions regarding quality and safety have been inadequately studied. Initial investigations of aquaponic produce quality have shown mixed results; while some attributes are similar among aquaponic and hydroponic produce, others differ (Crappé & Buysens, 2020; Ibrahim & Zuki, 2013; Piñero et al., 2020; Suhl et al., 2016; Yue et al., 2020). Even more scarce are studies of the sensory properties of aquaponic produce. The few available studies investigating sensory properties of aquaponic products have focused on liking rather than descriptive properties, with some studies showing an advantage of hydroponics (Ibrahim & Zuki, 2013), while others show no difference (Crappé & Buysens, 2020; Yue et al., 2020). Due to the limited and mixed evidence regarding the impact of aquaponics on produce quality, further research is merited (Suhl et al., 2016).

In addition to limited studies on aquaponic produce quality, further documentation of its safety is also needed to support commercial success. Although a number of studies have indicated that aquaponic products are as safe as products from traditional agricultural systems (Barnhart et al., 2015; Fox et al., 2012; Weller et al., 2020), safety and cleanliness are commonly cited as consumer concerns to aquaponics adoption (Milicic et al., 2017; Savidov, 2004; Short et al., 2017). Furthermore, documenting the safety of aquaponics is a key step in communicating risk to consumers and regulators (Klinger & Naylor, 2012). Nevertheless, recent studies have demonstrated that pathogen uptake from damaged roots into edible plant matter in aquaponic systems is biologically feasible (Wang et al., 2020, 2021); therefore, further studies investigating food safety risk are important to support aquaponics as a sustainable food production method.

Before the environmental benefits of aquaponic food production can be realized, a greater understanding of the impact of aquaponics on food safety and quality characteristics is necessary. While much of the research on aquaponics systems has focused on production and water remediation, relatively fewer studies have investigated the potential impact on produce quality. Therefore, the objective of this study was to characterize how aquaponics production impacts tomato quality and safety indicators.

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2 | MATERIALS AND METHODS

2.1 | Tomato samples

Tomatoes (*Solanum lycopersicum*) were started in soil and transferred to the aquaponic system at approximately 2.5 cm in height. Two varieties of tomatoes were grown to represent both a slicing tomato and a bite-size tomato: Early Girl (EG) (Park Seed, Greenwood, SC, USA, catalog no. 05329) and a Sugar Rush Hybrid (SRH) (Park Seed no. 52693). These varieties were chosen due to their popularity and indeterminate growth pattern. Six tomato seedlings of each varietal were suspended using 5-cm foam discs set within a 5-cm-thick styrofoam sheet in a 1.5 × 6.1 m raceway. A drain line from the aquaponic system consisting of three 750-L tanks (two tanks of yellow perch [*Perca flavescens*], at an average density of 9.33 kg/m^3 followed by one tank of 65 subadult calico crayfish [*Orconectes immunis*], with an average weight of 6.14 g) gravity fed the tomato raceway, as described elsewhere (Kralik et al., 2022). Late into year 2, liquid chelated iron (5%, 125 mL) (Rakocy et al., 1997) was added once monthly due to delayed growth and fruiting. Although iron supplementation appeared to enable fruiting and growth, quality and production volume were still negatively impacted. Because production volume was not sufficient to complete all tests, we grew and analyzed a third tomato crop in year 3. Despite variation in nutrient supplementation, we include results from all 3 years for transparency and to explore potential challenges associated with aquaponics produce quality. As a control comparison, six plants of the same tomato varieties were grown in standard potting soil in the same greenhouse, using standard commercial growing and fertilization (24-8-16 NPK ratio) techniques, alongside the aquaponics tomatoes.

Because we observed a potential impact of nutrient imbalances on tomato quality in year 2, we analyzed the nutrient content of approximately three fruiting tomato petioles with recently mature leaves attached from the terminal end of each tomato plant in both the aquaponic and soil systems during year 3. Samples were lightly rinsed and left to dry overnight prior to being packed into a perforated bag and shipped overnight for analysis of nitrate-N, phosphorus, potassium, magnesium, calcium, sulfur, sodium, boron, zinc, manganese, iron, copper, aluminum, and total nitrogen (A&L Great Lakes Laboratories, Fort Wayne, IN, USA). Samples were dried overnight at 100–105°C, then ground and sieved. Total nitrogen was analyzed based on the Dumas Method (90.03) (AOAC, 2019) using the rapid N exceed® nitrogen and protein analyzer (Elementar, Ronkonkoma, NY, USA). Mineral digestion was performed using an open vessel microwave (991-10D(e)) (AOAC, 2019) and microwave hot acid extraction procedure (SW846-3051A). Mineral analysis was conducted with inductively coupled argon plasma (ICAP) (985.01) (AOAC, 2019) run on a Thermo iCAP 6500 spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). Nitrate-N was analyzed using cadmium reduction and colorimetric analysis by flow injection (968.07) (AOAC, 2019) with a Lachat system.

Both the aquaponic tomatoes and soil-grown tomatoes were harvested the day before testing. Samples were selected based on absence of skin damage or injury, and uniform ripeness, regardless of size. All samples were lightly rinsed, dried, and stored at room temperature out of direct sunlight until testing. Tomatoes used for analysis of nutritional indicators were harvested using the same method with the exception that they were stored at −18°C until analysis.

2.2 | Coliform detection in soil and aquaponic environments

Soil and aquaponic water environments where tomato plants were grown and harvested were located within the same greenhouse. Samples were collected and processed prior to selection on two different media types to determine the presence of coliforms and *Escherichia coli*. For water, a 500-mL sample was taken from the midpoint of the aquaponics raceway. For soil, a 2-g sample was homogenized in 20 mL of 0.85% saline. MacConkey agar medium was used as a general indicator of coliforms. On May 24, 2021, 100 μL aliquots from each processed soil and water sample were spread plated on MacConkey plates, incubated at 37°C for 24 h, and then 96 colonies were randomly picked and streaked to isolation. Colony PCR was performed using the 16S rRNA primers 27 For (5′-AGR GTT TGA TCM TGG CTC A-3′) and 1492 Rev (5′-TAC GGY TAC CTT GTT AYG ACT T′3′). PCR conditions were 92°C denaturation for 120 s, 55°C annealing for 30 s, and elongation at 72°C for 90 s, repeated 29 times. ExoZAP-IT (Applied Biosystems, Waltham, MA, USA) was used to purify the PCR reactions prior to Sanger sequencing. The 16S rRNA gene sequences were BLASTED against the NCBI nucleotide database to identify the bacterial genus. mTEC medium was used to determine the presence of *E. coli* in the environments. One-milliliter aliquots were passed through a 0.2-μm filter and placed on mTEC agar medium. This was performed in replicates of five for each environment. Plates were incubated at 37°C for 24 h and scored for colonies with a magenta phenotype, indicative of *E. coli*.

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2.3 | Physical and quality indicators

Objective measurements for weight, color, texture, soluble solids, titratable acidity, and moisture were collected from the end of May to the end of October in all 3 years. The texture of both the EG and SRH tomatoes was analyzed using a texture analyzer (TIMS-Pro; Food Technology Corporation, Sterling, VA, USA) and a 6-mm probe. Firmness was determined as the distance (mm) the probe penetrated the sample before breaking the skin; skin strength (N) was determined as the maximum resistance measured prior to skin breakage. The firmness and skin strength were calculated as the average of measurements taken in three dispersed points on each EG sample. Due to the smaller size of the SRH variety, the firmness and skin strength were measured on one point for each sample. The L^*, a^*, and b^* (lightness, redness, yellowness) values of each sample were measured using a colorimeter (ColorFlex EZ; Hunter Labs, Reston, VA, USA). Sample weight was obtained using an analytical balance. Moisture content was calculated by determining the sample weight lost following freeze-drying (HarvestRight, North Salt Lake, UT, USA). Moisture content results were reported as a percentage of initial wet weight. Twenty biological replicates were performed for each of these analyses.

The titratable acidity of the tomato samples was determined by titration with sodium hydroxide (Gallander et al., 1991). The samples were homogenized using a food processor, diluted with deionized water, and titrated with 0.1 M NaOH until a pH of 8.2 was reached (Corning pH Meter 360i; Corning Life Science, Durham, NC, USA) (n = 20 EG samples; n = 10 pooled SRH samples consisting of three individual tomatoes each, due to their smaller size). To measure the brix of each sample, the samples were first homogenized using a food processor and strained to remove any excess skin particles. A handheld refractometer (model BX-1; Veegee, Vernon Hills, IL, USA) was used to measure soluble solids (n = 20). Following freeze-drying, additional freezing using liquid nitrogen, and pulverization, total extractable phenolic content of the tomato samples was determined using the Folin–Ciocalteu (FC) method as described by Nassar et al. (2015). Antioxidant scavenging capacity was determined using the ABTS method outlined by Nassar et al. (2015) (EG n = 5, SRH n = 5 pooled samples consisting of three tomatoes each).

2.4 | Sensory evaluation

No sensory data were collected during year 1 due to COVID-19-induced restrictions on human subject research. The sensory profile of the tomatoes was quantified using a semitrained descriptive panel in years 2 (October to early November) and 3 (mid-July to early September) (Veríssimo et al., 2021; Waehrens et al., 2016). Research protocols were approved by the university institutional review board, and written consent from the participants was obtained prior to participation in the study. During the first training session (approximately 1 h), panelists (year 2: n = 21, 11 female, mean age = 29.5 ± 15.0; year 3: n = 54, 36 female, mean age = 31.5 ± 15.2) were introduced to sensory science and their role as panelists. Panelists were screened for taste and smell sensitivity (ISO, 2012). Those that passed the taste and smell acuity screening were invited to the second training session (approximately 1 h). During the second session, panelists were familiarized with the rating system and the tomato attributes that would be evaluated in the taste test. The following attributes were evaluated: aroma—"green-viney" and "decaying vegetation"; flavor—"fruity," "musty/earthy," and "overall tomato"; basic tastes—salty, sweet, bitter, sour, and umami; texture—juicy, mealy, and firm (Table 1), based on relevant tomato descriptors identified by others (Hongsoongnern & Chambers, 2008; Li et al., 2021; Oltman et al., 2016). Participants were informed that each reference represented the "high" value on a 3-point rate-all-that-apply (RATA) scale. Panelists evaluated reference samples for each attribute and were encouraged to take notes about each sensation.

Within 1 week of the second session, qualified participants returned a third day to evaluate the four test samples: aquaponic EG, soil EG, aquaponic SRH, and soil SRH. Participants were refamiliarized with the attributes that were to be evaluated by being given reference samples for each attribute. Participants then completed a blind taste test in individual booths using a tablet. A "dummy sample" (Roma tomato) was the first sample evaluated by each participant to reduce first-position order effects (Lawless & Heymann, 2010). They were asked to evaluate each sample based on the attributes listed above using the three-point RATA scale (low, medium, high; participants could also leave an attribute unendorsed, effectively creating a 4-point scale) (Giacalone & Hedelund, 2016; Waehrens et al., 2016). Of note, 4-point RATA scales have similar discrimination ability as trained descriptive analysis panels (Nishida et al., 2021). The ballot was organized by modality with attributes being randomized within each modality across participants. Sample order was counterbalanced between participants. Data were collected using RedJade sensory software (RedJade Sensory Solutions LLC, Redwood City, CA, USA).

To complement descriptive testing, we also conducted acceptance testing in year 3 from the end of June to the beginning of October with untrained panelists in public locations; locations included outdoor parks, shopping

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TABLE 1 Tomato attributes used to train panelists for sensory testing of the aquaponic and soil-grown tomatoes.

Descriptor	Attribute definition	Reference sample
Green-viney	Associated with vegetables and cut green stems	Fresh cut tomato stems
Decaying vegetation	Associated with rotting plants, mildew, and mold; decomposing, rich, rotting smell	Decaying tomato
Musty/earthy	Attributed to damp soil, dirt-covered produce, and "cellar-like"	Peeled raw potato
Tomato flavor	Sweet, fruity, earthy, viney, ripe, and sour	Campbell's tomato juice
Sweet	Associated with sucrose	4% sucrose solution
Sour	Associated with citric acid	0.08% citric acid solution
Umami	Savory; flat, salty flavor enhancer	0.5% Pillsbury accent flavor enhancer solution
Bitter	Sharp or pungent taste or feeling; associated with caffeine	0.035% caffeine solution
Salty	Associated with salt or sodium chloride	0.60% NaCl solution
Fruity	Sweet, slightly floral, and sour	Ocean Spray white peach cranberry juice (diluted with water 1:1)
Juicy	The amount of liquid expressed during compression	Dole canned pineapple chunk
Mealy	Perception of fine, soft, somewhat round, and smooth particles evenly distributed; similar to gritty	Peeled, fresh pear
Firmness	Maximum force required to compress a food between teeth	Red seedless grape

centers, and the university campus. All protocols were approved by the university's institutional review board. Healthy adults ($n = 83$, 52 female, mean age = 35.9 ± 17.2) were recruited from the surrounding community. Participants that were under the age of 18, had known taste or smell issues, had known food allergies, or consumed tomatoes less than a few times a month were excluded from the study. Participants that completed the tests were provided a snack and gift card incentive. After reviewing and providing informed consent, the participants began the testing process using RedJade software. Participants were presented with five tomato samples: a Roma tomato from a local grocery store as a "dummy sample" in the first position, followed by aquaponic EG, aquaponic SRH, soil EG, and soil SRH in a counterbalanced order. Each sample was served in an individual disposable container labeled with a three-digit code. Participants were instructed to consume the sample and evaluate overall, appearance, taste, and texture liking using a 9-point hedonic scale where 1 = *Dislike extremely* and 9 = *Like extremely* (Lawless & Heymann, 2010). Participants were then asked to use check-all-that-apply (CATA) terms to describe the sample (fruity, musty/earthy, juicy, firm, mealy, sweet, bitter, sour, and salty). Between each sample, participants were instructed to rinse their mouths with water. A 30 s wait time was enforced between each sample using an onscreen timer. After evaluating the samples, participants answered basic demographic questions (gender and age).

2.5 | Statistical analysis

Data for weight, skin strength, firmness, moisture, titratable acidity, percent brix, and color (L^*, a^*, b^*) were all analyzed using independent samples *t*-tests comparing aquaponic and soil EG tomatoes and aquaponic and soil SRH tomatoes. RATA data from the descriptive study were first converted to a zero to three scale (unendorsed, low, medium, high) and analyzed using a paired *t*-test to explore differences in production methods with both varieties, consistent with previous validation of the use of parametric analyses of the 4-point RATA scale (Meyners et al., 2016). Additionally, blinded liking data were analyzed using a paired *t*-tests to explore differences in production methods between the two varieties. In cases where assumptions were not met for normality and homoscedasticity, a Mann–Whitney *U* test was used. CATA data were analyzed using a frequency table and Cochran's *Q* test.

3 | RESULTS AND DISCUSSION

In this study, we compared two tomato varieties from an aquaponic system with soil-grown counterparts on potential pathogen presence, physical composition, quality attributes, and sensory characteristics. While results varied across years, we found that the impact of aquaponics on tomato quality was generally minimal.

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TABLE 2 Bacterial diversity in aquaponics and soil systems.

Aquaponics		Soil	
Genus	**CFU (%)**	**Genus**	**CFU (%)**
Pantoea	1 (1%)	*Lelliottia*	1 (1%)
Hafnia	1 (1%)	*Pseudomonas*	6 (9%)
Klebsiella	5 (6%)	*Klebsiella*	16 (20%)
Citrobacter	5 (6%)	*Enterobacter*	17 (22%)
Plesiomonas	13 (16%)	*Raoultella*	38 (48%)
Enterobacter	*14 (17%)*		
Raoultella	*15 (18%)*		
Aeromonas	*29 (35%)*		

TABLE 3 Nutritional indicators of tomatoes grown in soil and the aquaponics system during year 1 of the study.

		Total phenolics	Antioxidant capacity
EG	Soil	0.39 ± 0.50	0.06 ± 0.03
	Aqua	0.27 ± 0.25[a]	0.08 ± 0.02
SRH	Soil	0.24 ± 0.15	0.10 ± 0.08
	Aqua	0.33 ± 0.30[a]	0.09 ± 0.03[a]

Note: Mean values and standard deviations are shown. No significant differences were detected.

Abbreviations: EG, early girl; SRH, sugar rush hybrid.

[a]Statistical differences between mean values were analyzed using the Mann–Whitney *U* test due to violations of normality and/or homoscedasticity.

3.1 | Safety

The average colony forming units (CFU) in each environment were 450 CFU/mL and 44 CFU/mg for aquaponics and soil, respectively, with some genera identical within both systems (Table 2). Although coliforms are used as indicators for possible contamination in water systems, most are nonpathogenic to humans (Washington State Department of Health, 2016). *Escherichia coli* was not found in either system. Of the identified bacteria, certain coliform species (*Enterobacter*, *Citrobacter*, *Hafnia*, and *Klebsiella*) were present, and while most of the genera are common in both soil and water habitats, *Aeromonas* and *Plesiomonas* are usually confined to freshwater systems (Tamames et al., 2010), as observed in our study. The observed decrease of Gram-negative bacterial counts and diversity in the soil samples can be explained by the use of a synthetic fertilizer in place of manure, thus limiting bacterial contamination from feces; moreover, Gram-positive bacteria such as *Bacillus* and *Streptomyces* dominate soil environments compared to Gram-negative bacteria, explaining the differences between bacteria species within each production system. Previous studies have found that aquaponic systems may have an equal or lower likelihood of introducing food safety hazards when compared to traditional agriculture, as water and produce samples were below the limit of detection for pathogens (Barnhart et al., 2015; Fox et al., 2012; Weller et al., 2020). Moreover, aquaponic-derived fish are not a high-risk source for pathogen growth or a vector to human illness, especially if fish introduced to the system are uncontaminated upon transfer (Fox et al., 2012). Although the possibility of pathogens in aquaponic systems is unlikely, it cannot be ruled out (Wang et al., 2020). Nevertheless, we provide additional evidence that produce from an aquaponic system contains no greater risk than soil-grown produce.

3.2 | Growth and composition

After verifying that the aquaponics tomatoes were as safe as the soil-grown tomatoes, we next examined the composition of the tomatoes. We observed no significant differences in total phenolic content or antioxidant capacity between the aquaponic and soil-grown tomatoes (Table 3). These findings align with those of Braglia et al. (2022) and can be assuring to health-conscious consumers, as both phenolics and antioxidants are among the popular health benefits of tomatoes (Luthria et al., 2006; Oltman et al., 2014). Suhl et al. (2016) observed that lycopene content in aquaponic tomatoes increased as systematic phosphorus and sulfur levels increased, thus emphasizing the importance of maintaining adequate mineral content of the aquaponic system.

In year 2, we observed delayed tomato growth and lack of fruiting in the aquaponic tomatoes of both varieties. Consequently, monthly liquid chelated iron supplementation was initiated approximately halfway through the second year (Rakocy et al., 1997), which improved tomato growth and fruiting in the aquaponic varieties. The improvement we observed following iron supplementation suggests that nutrient deficiencies were impeding growth and limiting quality among the aquaponic tomatoes. However, tomato volume was still insufficient to conduct all analyses, thus we grew a third tomato crop. To better understand how iron and other nutrients may influence tomato quality, we analyzed nutrient levels of tomato petioles in year 2 (Table S1). During year 2, deficiencies were noted in both systems, so nutrient analysis was continued in year 3 (Figure S2). Although the study was not initially designed to monitor nutrient levels, we report our results here to support future CEA studies. Because CEA is a sector of agriculture that is poised for dramatic growth due to its environmental, economic, and consumer benefits (Shamshiri et al., 2018), and the relatively scarce information connecting nutrient levels and quality outcomes, these data provide a foundational reference for future efforts to optimize CEA quality. We note that nutrients in an aquaponic system are inherently more variable than other CEA systems, given the dynamic nature of having multiple species in the same circulating system.

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TABLE 4 Color values of tomatoes grown in soil and aquaponics during years 1–3 of the study.

EG							
		L* (skin)	***a**** (skin)	***b**** (skin)	***L**** (flesh)	***a**** (flesh)	***b**** (flesh)
Year 1	Soil	41.58 ± 2.25	37.29 ± 1.85	27.53 ± 3.47	No data collected		
	Aqua	44.10 ± 2.27**	36.34 ± 1.90	32.01 ± 3.98**			
Year 2	Soil	37.84 ± 4.09	35.21 ± 4.30	26.35 ± 6.06	52.38 ± 11.06	27.39 ± 6.27	25.20 ± 1.93
	Aqua	48.99 ± 2.62***	36.00 ± 3.28	39.82 ± 3.21***[a]	65.99 ± 5.35**[a]	15.75 ± 7.24***	24.56 ± 2.24
Year 3	Soil	39.91 ± 4.50	37.94 ± 1.75	28.89 ± 3.83	48.28 ± 5.54	27.40 ± 6.64	25.64 ± 1.83
	Aqua	41.20 ± 2.69[a]	37.55 ± 1.90	29.59 ± 4.93	49.85 ± 5.35[a]	29.23 ± 4.87[a]	26.81 ± 1.85
SRH							
		L* (skin)	***a**** (skin)	***b**** (skin)	***L**** (flesh)	***a**** (flesh)	***b**** (flesh)
Year 1	Soil	26.72 ± 1.74	17.99 ± 1.31	11.95 ± 0.92	No data collected		
	Aqua	30.02 ± 0.77***[a]	18.48 ± 1.98	13.98 ± 1.26***			
Year 2	Soil	29.13 ± 1.48	17.44 ± 2.64	13.36 ± 2.39	27.86 ± 2.84	9.53 ± 3.00	15.62 ± 1.66
	Aqua	30.61 ± 1.17*	16.00 ± 1.46	16.09 ± 1.61**	29.86 ± 3.00	5.31 ± 3.50**	17.03 ± 1.91
Year 3	Soil	28.35 ± 0.83	15.37 ± 1.59	10.53 ± 1.62	23.07 ± 1.47	10.41 ± 1.98	12.10 ± 1.08
	Aqua	28.51 ± 0.69	14.31 ± 1.72	10.44 ± 1.12[a]	23.96 ± 1.88	13.41 ± 3.34*[a]	12.83 ± 1.66[a]

Note: Mean values and standard deviations are shown.

Abbreviations: *a**, redness; *b**, yellowness; EG, early girl; *L**, lightness; SRH, sugar rush hybrid.

[a]Statistical differences between mean values were analyzed using the Mann–Whitney *U* test due to violations of normality and or homoscedasticity.

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 5 Quality indicators of tomatoes grown in soil and aquaponics during years 1–3 of the study.

EG							
		Weight (g)	**Skin strength (N)**	**Firmness (mm)**	**Moisture (%)**	**TA (% acid)**	**Brix (%)**
Year 1	Soil	90.82 ± 30.00	7.95 ± 1.28	4.99 ± 0.93	87.09 ± 9.41	0.33 ± 0.04	4.61 ± 0.39
	Aqua	112.65 ± 27.59*	6.97 ± 2.22	5.96 ± 1.23**[a]	88.31 ± 4.01[a]	0.25 ± 0.05***	4.20 ± 0.69*
Year 2	Soil	No data collected					4.26 ± 0.54
	Aqua						2.71 ± 0.65***
Year 3	Soil	115.57 ± 47.39	7.99 ± 1.56	5.71 ± 1.16	87.35 ± 7.76	0.34 ± 0.01	4.88 ± 0.56
	Aqua	114.71 ± 38.80	7.42 ± 2.35[a]	6.46 ± 0.91*	87.09 ± 7.51[a]	0.22 ± 0.07***[a]	3.94 ± 0.56***
SRH							
		Weight (g)	**Skin strength (N)**	**Firmness (mm)**	**Moisture (%)**	**TA (% acid)**	**Brix (%)**
Year 1	Soil	11.09 ± 2.43	9.98 ± 2.71	4.17 ± 0.91	89.37 ± 1.50	0.33 ± 0.04	10.57 ± 0.63
	Aqua	8.52 ± 1.06***	9.24 ± 2.34	5.77 ± 0.92***	91.45 ± 1.78***	0.39 ± 0.06**[a]	7.26 ± 0.97*** [a]
Year 2	Soil	No data collected					7.11 ± 1.43
	Aqua						6.27 ± 1.18
Year 3	Soil	10.07 ± 1.69	11.47 ± 1.82	5.94 ± 1.41	89.10 ± 1.34	0.47 ± 0.03	9.36 ± 0.68
	Aqua	11.56 ± 1.82*	8.18 ± 1.83***	5.10 ± 1.07*	87.04 ± 5.53[a]	0.38 ± 0.04***	9.18 ± 1.30[a]

Note: Mean values and standard deviations are shown.

Abbreviations: EG, early girl; SRH, sugar rush hybrid.

[a]Statistical differences between mean values were analyzed using the Mann-Whitney U test due to violations of normality and or homoscedasticity.

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

3.3 | Quality indicators

We next compared tomato quality attributes that are directly observed by and important to consumers, such as size, color, texture, and flavor (Oltman et al., 2014). Tomato quality findings can be found in Tables 4 and 5. While we did observe differences in size, these differences were inconsistent across years and varieties. Due to limited tomato availability during year 2, only color and brix data were collected, as sensory testing was prioritized.

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Color differences were consistently seen between systems, with aquaponic tomatoes generally being lighter and more yellow. There may be a connection between color and nitrogen and potassium supplies, as potassium deficiencies (suspected in year 2) have been linked to blotchiness and improper color formation (Javaria et al., 2012). Furthermore, both insufficient and excess nitrogen have been associated with inadequate color development (Sainju et al., 2003). Others have also found color differences in aquaponic produce, with aquaponically-grown melon being lighter and greener than other production methods; moreover, aquaponic produce was lighter and more yellow when more nitrogen was supplied (Piñero et al., 2020). In year 2, we observed a whitening and hollowing of the EG flesh (Figure S1) and thus we began quantifying tomato flesh color. Nutrient deficiencies, such as potassium, induce a stress response and impact flesh development (Liu et al., 2020), and thus may explain the hollowing and whitening of the flesh. Given that potassium deficiencies are related to iron deficiencies (Xu & Shi, 2006) and the addition of chelated iron improved tomato growth in year 2, we hypothesize that nutrient deficiencies were responsible for the observed hollowing and whitening. Because consumers prefer redder tomatoes and perceive them as being riper (Oltman et al., 2014, 2016), elucidating the nutrient–color relationship is important to support consumer acceptance of aquaponics and other CEA systems.

Significant differences in skin strength and firmness were found between production methods and varieties, though these differences were inconsistent throughout the study. Texture differences for aquaponically-grown produce may ultimately depend on the crop and growing conditions, as there was no significant difference for aquaponically-grown basil when compared to basil grown hydroponically (Yue et al., 2020); however, less favorable textures have been found in cucumbers (Crappé & Buysens, 2020) and in lettuce (Ibrahim & Zuki, 2013) grown aquaponically when compared with other growing methods.

Both titratable acidity and brix (an indicator of soluble solids, such as sugars) are characteristics that impact the flavor profile—and therefore quality—of tomatoes (Baldwin et al., 1998; Oltman et al., 2014). Titratable acidity was consistently higher in the soil EG variety across years but was inconsistently significantly different among the SRH samples across years (Table 5). Percent brix was consistently higher in the soil-grown tomatoes compared with the aquaponic tomatoes in EG throughout the study and in SRH tomatoes only in year 1. These findings are similar to that of Suhl et al. (2016), who found aquaponic tomatoes to have lower soluble solids compared with hydroponic tomatoes. It is possible that the aquaponic tomatoes had greater and more consistent nitrogen supplies, as nitrogen is found in fish waste (Suhl et al., 2016) and may impact brix (Javaria et al., 2012); Suhl et al. (2016) found that low nitrogen supply ultimately improves the soluble solids content of tomatoes by increasing sugar content. Additionally, Piñero et al. (2020) found that aquaponically-grown melons had significantly lower concentrations of disaccharides when compared to the control. Aquaponic EG brix may have been lower in year 2 as a result of a suspected potassium deficiency in correlation with iron deficiency, as Javaria et al. (2012) found a positive correlation between potassium levels and soluble solids in tomatoes. There appears to be a connection between nutrient availability and brix; therefore, we recommend carefully monitoring and controlling nutrient levels to optimize quality and better understand the nutrient–quality relationships.

Moisture content was also inconsistent between varieties across years with soil SRH having a significantly lower moisture content in year 1 only. Bénard et al. (2009) found that tomatoes grown aquaponically had significantly lower dry matter and therefore more moisture than those that were hydroponically grown; however, both treatments were within the normal range for dry matter content for tomatoes. There may be a connection between nitrogen level and moisture content, as Bénard et al. (2009) found that higher nitrogen supply may result in lower dry matter content. It is hypothesized that the aquaponic tomatoes had higher and more consistent access to nitrogen than their comparison, potentially explaining the difference in moisture within the first year. As moisture content correlates with the juiciness of a tomato, a texture attribute that drives consumer acceptance of the fruit (Oltman et al., 2014), understanding the impact of production method on moisture content is important for consumer acceptance.

3.4 | Sensory descriptive analysis and acceptance outcomes

While objective indicators are useful for monitoring tomato quality, the consumer sensory experience ultimately determines acceptance. Therefore, we conducted both descriptive analysis and consumer acceptance evaluation to complement objective testing. The year 2 semitrained descriptive panel noted sensory differences between soil and aquaponic tomatoes (Table 6). Although aquaponic EG tomatoes were rated as less sweet, more umami, less fruity, and mealier in year 2, those findings were not observed in year 3. Importantly, the lower year 2 sweetness ratings in the aquaponic EG tomatoes correspond with our finding of lower percent brix (Table 5). While lower percent brix was also detected in

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TABLE 6 Descriptive analysis of tomatoes using semi-trained panelists and a three-point rate-all-that-apply scale.

		Green-viney	Decaying vegetation	Musty/earthy	Tomato flavor	Sweet	Sour	Umami	Bitter	Salty	Fruity	Juicy	Mealy	Firm
EG														
Year 2	Soil	1.1 ± 1.0	1.3 ± 1.1	0.9 ± 1.0	1.4 ± 1.0	1.6 ± 1.2	0.5 ± 0.9	0.6 ± 1.1	0.4 ± 0.6	0.3 ± 0.6	1.0 ± 1.2	2.0 ± 0.9	1.9 ± 1.1	0.8 ± 1.1
	Aqua	0.9 ± 1.0	1.5 ± 1.2	1.4 ± 1.2	1.3 ± 1.0	0.4 ± 0.8**	0.3 ± 0.6	1.5 ± 1.3*	0.9 ± 1.2	0.7 ± 0.9	0.3 ± 0.6*	2.4 ± 0.8	1.1 ± 1.0*	0.9 ± 1.1
Year 3	Soil	1.2 ± 1.0	0.9 ± 0.7	0.9 ± 1.1	1.6 ± 1.2	1.1 ± 1.2	0.4 ± 0.7	1.1 ± 1.1	0.5 ± 1.0	0.8 ± 0.9	0.7 ± 0.9	1.9 ± 1.1	1.2 ± 1.1	1.6 ± 1.0
	Aqua	1.3 ± 1.0	0.7 ± 0.9	0.9 ± 1.2	1.5 ± 1.1	1.3 ± 1.2	0.8 ± 0.9	0.7 ± 1.0	0.6 ± 1.0	0.4 ± 0.7*	0.9 ± 1.2	2.6 ± 0.7*	0.8 ± 1.0	0.6 ± 1.0**
SRH														
		Green-viney	Decaying vegetation	Musty/earthy	Tomato flavor	Sweet	Sour	Umami	Bitter	Salty	Fruity	Juicy	Mealy	Firm
Year 2	Soil	1.4 ± 1.0	0.3 ± 0.7	0.5 ± 0.9	1.9 ± 1.0	1.4 ± 1.3	1.2 ± 1.3	0.6 ± 1.0	0.1 ± 0.5	0.6 ± 1.0	1.1 ± 1.3	2.4 ± 0.9	0.5 ± 1.0	2.9 ± 0.4
	Aqua	1.4 ± 0.9	0.3 ± 0.8	1.0 ± 1.1	1.5 ± 1.0	0.9 ± 1.1	1.1 ± 1.1	0.6 ± 1.0	0.9 ± 1.2*	0.3 ± 0.9	0.7 ± 1.0	2.3 ± 0.8	0.6 ± 1.0	2.8 ± 0.4
Year 3	Soil	1.0 ± 0.8	0.5 ± 0.7	0.6 ± 0.9	2.1 ± 1.1	1.8 ± 1.3	0.4 ± 0.9	0.9 ± 1.0	0.5 ± 0.9	0.4 ± 0.7	1.0 ± 1.1	1.8 ± 1.1	0.2 ± 0.5	2.3 ± 0.9
	Aqua	1.3 ± 0.9	0.4 ± 0.7	0.5 ± 1.0	1.7 ± 1.3	1.8 ± 1.3	0.6 ± 1.0	0.9 ± 1.1	0.4 ± 0.7	0.7 ± 0.9	1.4 ± 1.3	2.0 ± 1.1	0.4 ± 0.7*	2.1 ± 1.0

*$p < 0.05$; **$p < 0.01$.

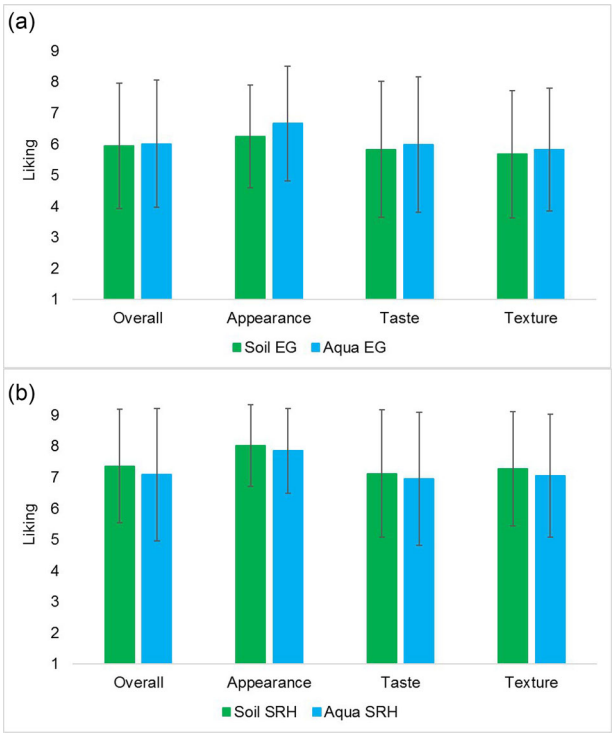

FIGURE 1 Liking scores of two varieties of aquaponic and soil tomatoes during year three. Bars represent the standard deviation. No significant differences were detected. (a) EG: early girl liking of attributes. (b) SRH: sugar rush hybrid liking of attributes. Participants used a 9-point hedonic scale, where 1 = *Dislike extremely* and 9 = *Like extremely*.

EG tomatoes in year 3, the panel did not find a significant difference. Based on this observation, we suggest that percent brix may be more sensitive to detecting differences than a semitrained panel and highlight the importance of using sensory evaluation to confirm objective findings. SRH aquaponic tomatoes were rated more bitter than soil-grown tomatoes in year 2 but not in year 3, while they were rated mealier in year 3 but not in year 2. Despite the minor differences noted by the panel, acceptance was not significantly impacted when aquaponic tomatoes were presumably sufficient in nutrients during year 3. No significant differences were detected in tomato attributes (measured using a CATA; data not shown) or in overall, appearance, taste, or texture liking of the aquaponic tomatoes compared to the soil-grown tomatoes (Figure 1). Our findings are consistent with others that have also found minimal liking differences between aquaponic and soil-grown tomatoes, cucumbers, and basil (Crappé & Buysens, 2020; Ibrahim & Zuki, 2013; Yue et al., 2020). However, liking differences have been observed when comparing aquaponics versus hydroponics (Ibrahim & Zuki, 2013) or warehouse versus greenhouse aquaponic systems (Yue et al., 2020), suggesting

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that growing conditions may impact acceptance in some situations.

3.5 | Strengths and limitations

Evaluating two tomato varieties across 3 years improves the generalizability of our findings. Furthermore, the collection of both objective and sensory measurements enables a comparison of standard quality control values with taste acceptance. Nevertheless, we acknowledge several limitations to the current study. The inconsistencies in quality outcomes we observed across years may be explained by nutrient imbalances and variable conditions that are inherent to aquaponics, as noted by others (Greenfeld, Becker, Bornman, et al., 2019; Yang & Kim, 2020). Furthermore, suspected nutrient deficiencies, especially in year 2, limit comparisons across years. Although the year 2 deficiencies introduce variation to our dataset, our studies quantify the consequences of possible nutrient imbalances and emphasize the importance of proper management. The variations we observed also suggest that the impact of aquaponics on produce quality may be explained by factors that can be addressed by the producer rather than a systematic impact of aquaponics. Understanding how nutrient levels impact produce quality can support CEA expansion.

4 | CONCLUSION

For the first time, we bring together microbiological, objective, descriptive analysis, and acceptance data to characterize the impact of aquaponics production method on produce quality. We found that aquaponic tomatoes are largely comparable to soil-grown tomatoes. While we observed differences in objective quality, particularly in color and brix, these differences varied by year and variety. Furthermore, blind consumer testing failed to detect differences in acceptability of either tomato variety. Together, our findings suggest a minimal impact of aquaponics on tomato quality. Because experienced and perceived quality influence consumer acceptance and taste is the top consideration for most consumers' food choices, our findings can support strategies that promote aquaponic produce as an attractive option for consumers. These findings also help position aquaponics as an environmentally friendly alternative that is as safe as conventional growing methods.

AUTHOR CONTRIBUTIONS

Brittany Kralik: Writing - review & editing; Writing - original draft; Investigation; Methodology; Formal analysis; Data curation; Conceptualization. **Natalie Nieschwitz**: Investigation; Writing - original draft; Writing - review & editing; Formal analysis; Data curation. **Kevin Neves**: Resources; Supervision; Writing - review & editing; Writing - original draft; Project administration; Funding acquisition; Conceptualization. **Nicholas Zeedyk**: Data curation; Formal analysis; Writing - original draft; Investigation. **Hans Wildschutte**: Resources; Supervision; Project administration; Writing - review & editing; Writing - original draft. **Jonathan Kershaw**: Funding acquisition; Conceptualization; Writing - original draft; Writing - review & editing; Methodology; Project administration; Supervision; Resources.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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