Survey of Physical, Chemical, and Microbial Water Quality in Greenhouse and Nursery Irrigation Water

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SUMMARY. The objective was to analyze the physical, chemical, and biological water quality in horticulture irrigation systems in 24 ornamental plant greenhouses and nurseries in the United States. At each greenhouse or nursery, water was collected from up to five points (“Sample Types”) which included 1) “Source” from municipal or private well supplies, 2) “Tank” from enclosed storage containers, 3) “Subirrigation” from water applied to crops in ebb-and-flood systems, 4) “Furthest Outlet” that were irrigation emitters most distant from the Source, and 5) “Catchment Basin” from open outdoor retention areas. On average, Source water had the highest physical and microbial quality of Sample Types including the highest ultraviolet (UV) light transmission at 86%, lowest total suspended solids (TSS) at 3.1 mg·L⁻¹, and lowest density of aerobic bacteria with 1108 cfu/mL of water. Average quality of recycled water from Subirrigation or Catchment Basins did not meet recommended levels for horticultural irrigation water for UV transmission (68% to 72% compared with recommended 75%), microbial counts (>100,000 cfu/mL compared with recommended <10,000 cfu/mL), and chemical oxygen demand (COD) (48.2 to 61.3 mg·L⁻¹ compared with recommended <30 mg·L⁻¹). Irrigation water stored in Tanks or applied at Furthest Outlets had lower physical and biological water quality compared with Source water. Level of aerobic bacteria counts highlighted a risk of clogged microirrigation emitters from microbial contaminants, with highest bacteria levels in recirculated irrigation water. The physical, chemical, and microbial water quality results indicate a need for more effective water treatment to improve biological water quality, particularly with recirculated irrigation.

Horticultural operations are increasingly using recirculating subirrigation systems and runoff water collected in catchment basins to supplement decreasingly available potable water sources for irrigation (Obreza et al., 2010). Irrigation water that is collected for use in catchment basins (capture-and-reuse) or recirculating (ebb and flood) irrigation systems are characterized by

elevated levels of physical, chemical, and biological contaminants that result in lower water quality, compared with potable water (Gilbert et al., 1980; Runia, 1994). When irrigating with low quality water, the combined physical, chemical, and microbial variables can result in microirrigation emitter and filter clogging and promote biofilm formation on critical surfaces within the water distribution systems (Bucks et al., 1979; Ravina et al., 1997). A report by Hong and Moorman

(2005) compiled research that identified 16 species of *Phytophthora* (including the plant pathogen *Phytophthora ramorum*), 26 species of *Pythium*, 10 viruses, waterborne plant pathogens, and other microorganisms in irrigation water samples collected from nursery and greenhouse operations.

Sanitation technologies are incorporated into horticulture irrigation systems to provide control of pathogens, improve plant health and prevent the development of secondary inoculum or protective overwintering structures (Agrios, 1997). These technologies include filtration, chlorination, copper ionization, ozonation, UV light, use of activated peroxygens, chlorine dioxide, heat, or other technologies to provide disinfection of irrigation water (van Os, 2009). Water quality variables such as suspended particles, dissolved organic and inorganic molecules, and microbes create a demand on sanitizing agent active ingredients, thereby reducing the efficacy of water treatment technologies for control of microbes, pathogens, and algae (Copes et al., 2004; Ravina et al., 1997; Sutton et al., 2006).

Monitoring of biological, physical, and chemical variables is necessary to ensure water quality is adequate for its intended use. For example, a standard evaluation for health and operational safety at food and beverage processing and recreational swimming facilities monitors biological variables such as counts of aerobic bacteria and fungi to indicate contamination or ineffective treatment [American Public Health Association (APHA), 1995; Maier et al., 2009]. The reduction of bacterial counts from water samples collected before vs. after water treatment is used as a measure of effective control by a sanitizing agent, according to the U.S. Environmental Protection Agency (USEPA, 1999). Physical

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
1	micron	μm	1
1000	mmho/cm	μS·cm ⁻¹	0.0010
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

contaminants from plant debris, peat-moss, sand, and insoluble salts can restrict water flow, create a sanitizing agent demand, reduce UV transmission, and shield target pathogens from contact with a sanitizer (Copes et al., 2004; Gauthier et al., 1999; Pettygrove and Asano, 1985; Pirovanni et al., 2004; Rogers et al., 2003). Chemical aspects of water quality, including pH, total dissolved solids, alkalinity, and nitrogen, can decrease the efficacy of sanitizing treatment to provide pathogen and pest control. High solution pH and reduced forms of nitrogen in organic and inorganic compounds, such as ammonium in water-soluble fertilizers, can reduce the availability of strong oxidizers such as hypochlorous acid (APHA, 1995; Feben and Taras, 1955; Heibling and VanBriessen, 2008; Tanwar et al., 2008).

Surveys have been conducted to assess chemical water quality (Argo et al., 1997) and pathogen presence in ornamental greenhouses and nurseries (Hong and Moorman, 2005). Water quality information is lacking on whether levels of water contaminants such as suspended solids, aerobic bacterial density, and COD meet recommended guidelines. If physical, chemical, and microbial load are outside of recommended guidelines, there is increased risk that treatment technologies will not provide effective control of target pathogens, algae, and biofilm in recirculated irrigation systems.

The objective of this study was to quantify physical, chemical, and microbial load and overall sanitizing demand at key sampling points within irrigation systems, using a field survey approach at multiple greenhouse and nursery locations. These values were compared against published irrigation guidelines for effective sanitation treatment for control of pathogens, algae, and biofilm, and for adequate nutrient management of horticultural crops.

Materials and methods

Field surveys were conducted at 24 greenhouse and nursery ("Locations") across 11 states in the United States, during a period of active crop production from April to July 2009. Surveyed Locations had an average production area of 985,546 ft² (Table 1), ranging from 72,000 to 6,533,989 ft². The reported average daily water use

among the Locations was 160,724 gal with a range of 6001 to 1,000,105 gal. Overall, an average of 33% or 43,605 gal (range from 0% to 100%, or 0 to 1,000,105 gal) was from recycled water, defined as Subirrigation (recirculated ebb-and-flood) or Catchment Basin (a combination of rainwater, runoff, and other sources). The sampled population of greenhouse and nursery Locations produced a variety of seedling plug and cutting transplants and finished containerized ornamental crops. Growers who managed recycled or treated irrigation, and who had participated in previous water quality extension workshops by the authors in several U.S. states, were selected to participate if they were willing to comply with a standardized sample collection and handling protocol.

Water samples were collected at points within each Location that represented up to five Sample Types: Source, Tank, Subirrigation, Furthest Outlet, and Catchment Basin. Source represented municipal supply or well water that was collected from an inline main (6–10 inches) pipe or pressurized expansion tank at the first access point in each nursery (most upstream access point within each of the Locations). Tank water was collected from enclosed containments of treated (chemical sanitizer, filtration, or both) irrigation solution before going through distribution plumbing. Furthest Outlet was the irrigation solution at the point of application to the crop located furthest away from the Source, after passing through the distribution plumbing, and was collected from overhead, drip, or hand-held nozzles. Subirrigation samples were collected from recycled ebb-and-flood irrigation during a flood cycle and before filtration or sanitizer treatment. Catchment Basin samples were collected from an outdoor, open surface area that received runoff and recycled irrigation water and from the depth of the pump intake valve, before filtration or treatment.

To determine the effect of water treatment on microbial density in irrigation water during crop production, counts were made on additional samples collected from Locations that treated water with sanitizer injection or membrane filtration (Table 1). Eight Locations provided water treatment to recycled irrigation, nine Locations treated well or municipal Source water, and seven Locations did not use

sanitizers or membrane filtration. Samples collected at the closest sampling points before and after sanitizer or membrane filtration were identified as pretreatment and posttreatment. Pretreatment samples from Source water had not received any sanitizer or membrane filtration after water entered the greenhouse, whereas pretreatment samples from Subirrigation and Catchment Basins were collected after an irrigation event, before additional filtration or sanitizer treatment. Recycled water was reported as the percentage of daily water used at each Location that was collected and used again for irrigation.

The experimental design was a split plot with Location as the main plot and Sample Type as the subplot. Effects were analyzed using analysis of variance using GLM (SAS version 9.1; SAS Institute, Cary, NC) including Location (24 levels), Sample Type (5 levels), and Sample Type × Location interaction, where the sampling time during the day within each Location was a random variable used as the error term. Because of differences in irrigation system design, not all of the 24 Locations had all five Sample Types. Additional analysis of pretreatment and posttreatment was conducted using MIXED (SAS version 9.1).

Techniques for collection, handling, and laboratory processing followed standard methods (APHA, 1995). Three replicates of 350-mL samples were collected in Whirl-Pak™ (Nasco, Modesto, CA) sterile collection bags from the five Sample Types. A total of 15 samples were collected at each of the Locations, by a trained grower or supervised employee during 1 d of production. Each Location was sampled once during the 6 weeks of collection and analysis. Four Locations per week shipped their samples overnight to the University of Florida in insulated coolers with ice packs and digital data loggers (HOBO; Onset Computers, Bourne, MA) to ensure environmental stability and sample integrity during collection and shipment. All samples were received for processing and analysis within 20 h from the time they were collected and were maintained between 22 to 25 °C.

Physical water quality was determined by TSS, as described in Current Method 2540 D (APHA, 1995). A vacuum pump (model 4144; Emerson, St. Louis, MO) applied a constant

Table 1. Descriptive characteristics for the production environments from each greenhouse or nursery (Location) included in the survey of irrigation quality. Each Location is listed by row and identified by the code number (1–24) presented in the first column. Each row represents a different Location, and specifies the production area, water sources, and irrigation technologies used.

Code	State	Production area ² (ft ²) ^y	Main water source ^x	Well depth (ft) ^y	Daily water used ^w (gal) ^y	Recycled % ^v	Filtration	Filter pore-size (μm) ^y	Treatment system	Acid
1	Florida	174,235	Well	141	20,002	0	Screen	>300	Calcium hypochlorite	Sulfuric
2	Florida	999,999	Well	440	100,011	30	Screen	>1,000	Calcium hypochlorite	None ^u
3	Colorado	78,749	Municipal	None ^u	10,001	0	Centrifuge	None ^u	Calcium hypochlorite	Phosphoric
4	Florida	500,005	Well	180	135,014	0	Screen	>300	Chlorine dioxide	None
5	Florida	653,003	Well	331	64,267	0	Centrifuge, screen	120	Sodium hypochlorite	Sulfuric
6	Michigan	600,001	Municipal	None	1,000,105	75	Screen, paper	28	Sodium hypochlorite, ozone	Sulfuric
7	Florida	72,000	Well	131	35,004	90	Screen	>300	Copper ionization inline	None
8	Florida	900,002	Well	200	80,008	0	Sand, screen	100	Copper ionization inline	Sulfuric/phosphoric
9	New Jersey	799,995	Well	131	6,001	0	Screen	100	Copper ionization inline	None
10	North Carolina	6,533,989	Pond	None	1,000,105	100	Centrifuge, sand, paper	28	Copper ionization inline	None
11	California	3,999,994	Pond	None	490,052	100	Centrifuge, screen	100	Copper ionization inline	Sulfuric/phosphoric
12	New Hampshire	200,004	Well	801	20,002	75	Centrifuge, screen	100	Copper ionization tank	None
13	New Hampshire	121,998	Well	125	45,005	50	Paper	28	Filtration only	Sulfuric
14	New Hampshire	93,000	Well	121	30,003	50	Centrifuge, screen	100	Filtration only	Sulfuric
15	California	2,599,999	Municipal	None	60,006	0	Screen	None	Filtration only	None
16	Michigan	200,004	Well	89	90,010	40	Screen	100	Filtration only	Nitric
17	Florida	1,012,474	Well	26	15,002	0	Screen	>300	Filtration only	Sulfuric
18	Michigan	729,997	Well	112	80,008	10	Paper	18	Filtration only	Sulfuric
19	Minnesota	none	Well	200	None	None	Centrifuge	>300	Filtration only	None
20	Michigan	479,995	Well	121	55,006	0	Centrifuge	100	Hypochlorous acid	Sulfuric
21	Florida	232,124	Well	26	6,001	0	Centrifuge	>300	Peroxyacetic acid	Sulfuric
22	New Jersey	769,996	Well	49	250,026	15	Screen, paper	28	Peroxyacetic acid	Sulfuric
23	Michigan	215,999	Well	161	35,004	0	Reverse osmosis	<1	Peroxyacetic acid	Sulfuric
24	New Mexico	699,998	Well	98	70,007	40	Reverse osmosis	<1	Reverse osmosis	None

²Size of the production area from which irrigation was sampled.

^y1 ft² = 0.0929 m², 1 ft = 0.3048 m, 1 gal = 3.7845 L, 1 μm = 1 micron.

^xWhere the irrigation originated; well was irrigation pumped from below ground, municipal was treated city tap water and pond was irrigation collected in a Catchment Basin.

^wEstimated total daily irrigation volume used, as reported for each Location.

^vPercentage of irrigation runoff that was captured and recirculated in a subirrigation loop or held in a Catchment Basin.

^uValue was not reported.

suction of 200 kPa to filter each 200 mL sample through a 4.25 cm preweighed GF/C 0.45 μm glass fiber filter (Whatman-GE, Maidstone, UK) to recover all suspended particles (particles smaller than 0.45 μm were assumed to be dissolved solids). Organic carbon was analyzed using the loss on ignition procedure where weighed filters from previous TSS analysis were ignited in a muffle furnace at 550 $^{\circ}\text{C}$ to volatilize the organics and then reweighed according to standard methods (APHA, 1995). The UV transmission was determined by spectrophotometry at 254 nm, as described by Chang et al. (1998) using a spectrophotometer (SpectraMax Plus model 384; Molecular Devices, Sunnyvale, CA) and an analytical software package (SoftMax-Pro, Molecular Devices).

Chemical water quality was evaluated using several testing methods outlined by the USEPA (2004). The COD was determined by colorimetric analysis using a digital colorimeter (ORION 4000; Thermo-Fisher, Barrington, IL) and COD AQUAfast IV test ampoules containing potassium-dichromate and mercuric sulfate (Thermo-Fisher). Digestion with a COD block incubator (Hach, Loveland, CO) was followed by analysis using the closed reflux colorimetric method 5220 B (APHA, 1995). Chemical measurements of pH, alkalinity, dissolved oxygen and electrical conductivity (EC) were conducted using methods described by the Association of Agricultural Chemists (AOAC), 1999. Chlorine demand was evaluated at 2 min using standard method 4500-Cl G (APHA, 1995).

Microbial analysis was performed using a dry rehydratable culture substrate, direct count plates (PetrifilmTM; 3M Microbiology, St. Paul, MN) formulated for aerobic bacteria cultures or yeast and molds. Each culture contained a dehydrated substrate mounted on a flexible card where microbial colonies are detected and counted with the aid of a color indicator to enumerate living microbial densities. Irrigation samples were transferred into culture immediately after samples were removed from insulated shipping coolers and allowed to reach to room temperature. Microbiological methods followed official methods: 990.12, Petrifilm Aerobic Count Plates and 997.02, Yeast and Mold Count Plate (AOAC, 1999). Serial dilutions

were carried out at 1 to 10^8 dilutions for aerobic bacteria and one to 10^4 for yeasts and molds, and sterilized water was used as control. Each serial dilution was cultured on aerobic bacteria as well as yeast and mold substrate with three replicates each. Cultures were incubated at 74 $^{\circ}\text{F}$ in the dark for 3 to 7 d, until counts were stable. Magnification ($\times 10$) was used to obtain colony counts for each culture. Counts were made from the selected dilution, which resulted in 10 to 250 cfu/mL on the aerobic count plates and from 10 to 150 cfu/mL on yeast and mold count plates.

Results and discussion

Physical water quality variables had significant main effects for Sample Type and Location with TSS and UV transmission variables, and main and interaction effects for organic carbon. Clogging risk was evaluated using the Bucks et al. (1979) clogging index for microirrigation systems, whereby levels of physical, chemical, and biological contaminants were each rated a value from 0 (no risk) to 10 (severe risk); a combined total of 10 or less represented low clogging risk; a combined total of 20 or more would represent a severe risk and indicate need for treatment. TSS level was insufficient to indicate a physical clogging risk according to the Bucks et al. (1979) scale (Table 2). A TSS below 5 $\text{mg}\cdot\text{L}^{-1}$ is recommended when reuse water will be treated with a chemical oxidizer (USEPA, 1999), and this recommended level was exceeded for Furthest Outlet, Subirrigation, and Catchment Basin samples. Water used to irrigate food crops in Florida has a TSS limit of 5 $\text{mg}\cdot\text{L}^{-1}$, with a limit of 20 $\text{mg}\cdot\text{L}^{-1}$ for nonfood crops (USEPA, 2004) that would apply to the ornamental crops grown in survey Locations.

The average physical water quality for Sample Types other than the Source did not meet published guidelines for irrigation use in terms of organic carbon and UV transmission (Table 2). The guideline for effective disinfection with UV treatment is a UV transmission of at least 75% at the 254-nm wavelength (Newman, 2004). Lower water quality is indicated if total organic carbon is above 2 $\text{mg}\cdot\text{L}^{-1}$ because UV transmission and efficacy of sanitizing agents both decrease (Chang et al., 1998; USEPA,

1999). Samples collected from the Source had the highest physical quality among the Sample Types in terms of higher UV transmission and lower levels of TSS and organic carbon compared with Subirrigation and Catchment Basin samples. Although TSS in Source water samples was below 10 $\text{mg}\cdot\text{L}^{-1}$ in all Locations, six Locations had organic carbon levels above the recommended 2 $\text{mg}\cdot\text{L}^{-1}$ (between 2.1 and 7.1 $\text{mg}\cdot\text{L}^{-1}$). Only one Location had low physical quality from the Source indicated by a low UV transmission that was below the recommended 75%. At all of the other Locations the higher UV transmission (above 75%) indicated suitability of sanitation with UV treatment. Physical water quality variables did not differ ($P > 0.05$) between Subirrigation and Catchment Basins or between Tank and Furthest Outlet. After the Source, the decreased UV transmission may have resulted from a combination of TSS and dissolved micronutrient chelates and fertilizer dyes. Organic carbon comprised between 51% and 69% of TSS, depending on the Sample Type, with the remaining 31% to 49% consisting of nonignitable mineral particulates. Because the organic carbon component of TSS can be oxidized, samples with a high proportion of organic carbon would be likely to increase sanitizing agent demand.

There was a moderate risk of clogged drip emitters from chemical contaminants according to the Bucks et al. (1979) scale. However, alkalinity, total dissolved solids, and EC of Source water were within the water quality recommendations for use on floriculture crops. Chemical water quality variables had significant main effects for Location for all chemical water quality measurements. Sample Type affected chemical water quality variables other than alkalinity (Table 2). Management of pH is important both for nutrient management and its effects on activity of sanitizers such as chlorine (decreasing the availability of the strong sanitizing form of hypochlorous acid with increased pH) and copper (decreased solubility with increasing pH). Average pH was outside the recommended guidelines for Source and Catchment Basin. Appropriate treatment to decrease alkalinity and pH would include acid injection and possibly reverse osmosis. Total

Table 2. Analysis of variance (ANOVA) of irrigation quality results from the surveyed population of 24 greenhouses and nurseries (Locations). Irrigation quality variables were analyzed by Location, Sample Type (Source, Tank, Furthest Outlet, Subirrigation, or Catchment Basin), and their interaction (Location $\times$ Sample Type). Least-squared means are presented for each Sample Type Values followed by a superscript notation indicate they are outside recommended guidelines (see footnotes below).

Water quality variable	ANOVA effect ^z				Least-square means by Sample Type					Recommended ranges
	Sample Type	Location	Sample Type × Location	Source	Tank	Furthest Outlet	Subirrigation	Catchment		
								Basin		
Physical										
Total suspended solids (mg·L ⁻¹) ^y	***	***	NS	3.1 a ^x	4.4 a	5.5 a	9.6 b		9.7 b	<30 ^w
Organic carbon (mg·L ⁻¹)	***	***	**	2.0 a	2.9 ^v a	3.8 ^v a	4.9 ^v b		6.2 ^v b	≤2 ^v
Ultraviolet transmission (%) ^u	***	***	NS	86 a	75 bc	76 b	68 ^c		72 ^c bc	>75% ^t
Chemical										
Alkalinity (mg·L ⁻¹) ^s	NS	***	NS	128 c	59 ab	130 bc	55 a		120 c	<150, <300 ^r
Total dissolved solids (mg·L ⁻¹)	*	***	NS	425 a	528 ^r ab	502 ^r ab	676 ^r b		354 a	<480, <960 ^r
pH	***	***	NS	7.6 ^q cd	6.8 ab	7.3 bc	6.3 a		8.1 d	<7.5 ^q
EC (μS·cm ⁻¹) ^z	**	***	NS	660 a	840 ^r ab	787 ^r ab	1110 ^r b		553 a	<750, <150 ^r
Microbial										
Aerobic bacteria (cfu/mL) ^p	***	**	**	1,108 a	65,229 ^o ab	184,728 ^o b	117,431 ^o b		435,336 ^o b	<10,000 ^o
Yeast and mold (cfu/mL)	*	**	NS	6 a	871 a	94 a	3,181 b		980 a	ND ⁿ
Overall sanitizing demand										
Chemical oxygen demand (mg·L ⁻¹)	***	**	NS	12.0 a	37.7 ^w bc	30.5 ^w b	48.2 ^w cd		61.3 ^w d	<30 ^w
Chlorine demand at 2-min (mg·L ⁻¹)	**	NS	NS	1.4 a	8.7 b	6.4 ab	8.2 ab		3.2 ab	ND
Clogging risk										
Physical				0	0	0	0		0	<10 ^m
Chemical				6	5	5	6		5	<10 ^m
Microbial				2	10 ^m	10 ^m	10 ^m		10 ^m	<10 ^m
Total				8	15 ^m	15 ^m	16 ^m		15 ^m	<10 ^m

^aStatistical significance indicated by NS, *, **, *** are NS or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

^y1 mg·L⁻¹ = 1 ppm; 1 $\mu\text{S}\cdot\text{cm}^{-1}$ = 0.0010 mmho/cm.

^xMean separation performed using Tukey's honestly significant differences at $P \leq 0.05$.

^wGuidelines from U.S. Environmental Protection Agency (2004).

^vRecommendations provided by Chang et al. (1998).

^uUltraviolet light transmission.

^rRecommendations from Newman (2004).

^sEquivalent concentration of calcium carbonate (CaCO₃) that would need to be neutralized by a strong acid.

^tGuidelines ranges for plug production and floricultural crops from Whipker et al. (2003).

^pRecommendations from Copes et al. (2004).

^qColony forming units; 1 cfu/mL = 29.5735 cfu/fl oz.

^oRecommendations from Rogers et al. (2003).

ⁿNo data.

^mGuidelines from Bucks et al. (1979).

Table 3. Analysis of variance table for aerobic bacteria and yeast and mold densities for each greenhouse and nursery (Location) surveyed. At each Location, samples were collected at the Source and Furthest Outlet. For Location 7, there were two Source and Furthest Outlet irrigation circuits, which were analyzed separately. Locations 20 and 24 did not have Furthest Outlet sampling points and were not included. The reported densities of aerobic bacteria and yeast and mold are least-square means for each Location, with statistical comparison between Source and Furthest Outlet by Location.

Location code	Treatment ^z	Recycled (Catchment Basin or Tank) ^y	Aerobic bacteria (cfu/mL) ^x			Yeast and mold (cfu/mL)		
			Source	Furthest Outlet	Significance ^w	Source	Furthest Outlet	Significance
1	Yes	No	1,203	1	NS	0	0	NS
2	Yes	Yes	1,066	576,825	***	12	560	*
3	Yes	No	1	1	NS	0	0	NS
4	Yes	No	1,522	12,504	NS	0	42	NS
5	Yes	Yes	9,376	2,463,801	***	141	31	NS
6	Yes	Yes	0	1,100	NS	0	153	NS
7	Yes	No	92	217,884	***	4	459	**
7	Yes	Yes	92	395,213	***	4	0	NS
8	Yes	No	11	103,948	***	0	8	NS
9	Yes	No	236	570	NS	1	0	NS
10	Yes	Yes	14,460	65,142	***	123	730	*
11	Yes	Yes	1	172,732	***	0	69	NS
12	Yes	No	340	54,602	***	0	2	NS
13	No	Yes	33	206,016	***	0	2,910	***
14	No	Yes	3	34,303	***	0	8,508	***
15	No	No	8,714	671	NS	0	60	NS
16	No	Yes	232	199,469	***	7	107	NS
17	No	No	1,135	253	NS	0	0	NS
18	No	No	20,722	28,500	***	7	0	NS
19	No	No	9	1	NS	0	0	NS
21	Yes	No	248,054	294	***	688	1,447	NS
22	Yes	Yes	21	35,604	***	0	13,435	***
23	Yes	No	38	18	NS	0	196	NS
Location					***			***
Sample Type					***			*
Treatment					NS			NS
Recycled					***			***
Location × Sample Type					***			***
Treatment × Recycled					***			NS

^xIndicates whether chemical sanitation was used (yes) or not used (no) between the Source and Furthest Outlet.

^yIndicates whether irrigation water was collected and held in a Catchment Basin or Tank between the Source and Furthest Outlet (yes) or was not held in a Catchment Basin or Tank (no).

^zColony forming units; 1 cfu/mL = 29.5735 cfu/fl oz.

^wStatistical significance indicated by NS, *, **, *** are either not significant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

dissolved solids were measured with an EC meter, in contrast with filtered TSS, which represented particles larger than 0.45 μm in diameter. Total dissolved solids and alkalinity can result in precipitation of inorganic components and combined compounds such as calcium carbonate. Total dissolved solids and EC for Source water were within recommended values for production ornamental crops (Whipker et al., 2003). Higher total dissolved solid and EC values in Tank, Furthest Outlet, and Subirrigation may not indicate a problem because these Sample Types included water-soluble fertilizer that was injected immediately after the Source. According to criteria from Bucks et al. (1979), the Source and Subirrigation had a 6/10

chemical risk of emitter clogging and a rating of 5 for other Sample Types.

Source samples had the lowest aerobic bacteria counts of all Sample Types, and Subirrigation samples had the highest yeast and mold counts. There were significant main effects for Sample Type and Location for aerobic bacteria as well as yeast and mold, with a significant interaction for aerobic bacteria. Microbial water quality variables for Source water were within the recommended guidelines, whereas Tanks, Furthest Outlet, Subirrigation, and Catchment Basin had aerobic bacteria above the recommended 10,000 cfu/mL (Table 2). There was a severe microbial clogging risk from Tank, Furthest Outlet, Subirrigation, and Catchment Basin, with a biological

contamination index of 10/10 (Bucks et al., 1979). Biofilms are microbial multicellular structures, often consisting of bacteria, fungi, and algae and extracellular polymers that are produced and excreted by them used to establish on any wet surface including pumps and pipe materials (Kerr et al., 1999; Rogers et al., 2003), plants, fruit, and vegetables (Carmichael et al., 1999). High levels of microbial growth indicate limited water treatment efficacy and the potential to harbor plant pathogens in biofilm.

The Source had low COD and chlorine demand compared with other Sample Types, which did not meet COD guidelines (Table 2). Sample Type and Location significantly affected COD, and chlorine demand was

Table 4. ANOVA table for effect of sanitation treatments on the cfu/mL of aerobic bacteria and yeasts and molds. Samples were collected immediately before (Pretreatment) and immediately after (Posttreatment) each sanitation treatment. The reported density of aerobic bacteria and yeast and mold are least-square mean cfu/mL for each Location followed by significance between pretreatment and posttreatment.

Location	Sanitation treatment	Aerobic bacteria (cfu ^z /mL) ^y			Yeasts and molds (cfu ^z /mL) ^y		
		Pretreatment	Posttreatment	Significance ^x	Pretreatment	Posttreatment	Significance ^x
1	Calcium hypochlorite	224,818	1	***	33	0	*
2	Calcium hypochlorite	325,151	19,791	***	33	17	NS
3	Calcium hypochlorite	1	1	NS	0	0	NS
4	Chlorine dioxide	1,522	286	NS	0	2	NS
5	Sodium hypochlorite	215,705	40	***	10	3	NS
6	Sodium hypochlorite	0	0	NS	0	0	NS
6	Ozone circulation tank	940	478	NS	149	49	NS
7	Copper ionization inline	92	46	NS	4	2	NS
8	Copper ionization inline	104	25,606	***	0	34	*
9	Copper ionization inline	236	665	NS	1	0	NS
10	Copper ionization inline	6,516	65,142	NS	315	730	NS
11	Copper ionization inline	393,443	1,462,866	***	484	140	NS
12	Copper ionization tank	340	39,689	***	0	1	NS
21	Peroxyacetic acid	261,683	300	***	1,405	1	***
21	Peroxyacetic acid	86,201	9	***	75	10	*
22	Peroxyacetic acid	33,015	122,724	NS	18,002	15,841	NS
23	Peroxyacetic acid	75	58	NS	0	0	NS
24	Reverse osmosis	149,027	65,183	***	372	28	***
Treatment			***			***	
Location			***			***	
Treatment			***			***	
×Location							

^zColony forming units (cfu).

^y1 cfu/mL = 29.5735 cfu/fl oz.

^xStatistical significance indicated by NS, *, **, *** are either not significant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

affected only by Sample Type. Sanitizing agent demand can be quantified directly by measuring the difference between applied and residual active ingredient concentration when a sanitizer is injected into a water sample or indirectly by the COD. The COD represents the amount of oxygen required to completely oxidize contaminants in water and is therefore correlated with the required sanitizing agent concentration (Tanwar et al., 2008). Biodegradable organic matter in reused irrigation water and industrial effluent is monitored for compliance with COD to ensure the sanitizing agent demand is not too high (USEPA, 2004). The COD was highest from Catchment Basin samples, although Catchment Basins had a low chlorine demand compared with most other Sample Types. The low chlorine demand probably occurred in Catchment Basin samples compared with Subirrigation, Tanks, and Furthest Outlet samples because the latter three Sample Types would have contained nitrogen from water-soluble fertilizer. Published guidelines for chlorine demand suggest a minimum free chlorine residual

of 1 mg·L⁻¹ after a 30-min contact time (USEPA, 1999). However, this free chlorine level is unlikely to occur when reduced forms of nitrogen such as ammonium fertilizer are present, resulting in complexed chlorine. Chlorine demand of 8.2 mg·L⁻¹ for Subirrigation water, for example, can be interpreted as a requirement for 10.2 mg·L⁻¹ of applied chlorine to provide 2 mg·L⁻¹ of residual free chlorine.

Changes in microbial water quality from Source to Furthest Outlet (Table 3) indicated a general trend of declining water quality as water was distributed through irrigation lines. For both aerobic bacteria and yeast and mold counts, there were significant main or interaction effects for Location, Sample Type, and "Recycled" (a yes/no variable corresponding to whether water was captured and reused between the Source and Furthest Outlet). In one case (Location #21), there was a significant reduction in aerobic bacteria counts from Source to Furthest Outlet (Table 3), where the Source was from a shallow well followed by treatment with peroxyacetic acid (Table 1). Significant

increases in aerobic bacteria between Source and Furthest Outlet occurred in 13 Locations, despite chemical treatment in nine of these cases (Table 3). In general, there were higher microbial counts in recycled irrigation. However, there were exceptions such as the high counts in Locations 21, 7, and 8 despite no recycling.

The change in total microbial counts at sampling points before and after sanitizer injection was used as a bioindicator to monitor the capability of the water treatment system to control microorganisms at each Location. Interpretation of the efficacy of the treatment systems is limited by only 1 d of sampling and limited replication of technologies between Locations. There was a significant interaction between Location and Treatment for aerobic bacteria as well as yeasts and molds (Table 4). Eight Locations exceeded the recommended 10,000 cfu/mL for aerobic bacteria pretreatment, and in four of those cases the posttreatment level was below 10,000 cfu/mL. Irrespective of pretreatment counts of aerobic bacteria were above 10,000 cfu/mL at

the posttreatment sampling point, including one Location with calcium hypochlorite, four with copper ionization, one with peroxyacetic acid, and one with reverse osmosis. The high posttreatment bacteria counts indicated several cases where treatment systems were not providing biological irrigation quality within recommended guidelines.

Conclusions

Monitoring of the physical, chemical, and microbial water quality can improve the efficacy of treatment with reliable control of pathogens without causing corrosion of pumps and equipment (Chang et al., 1998) and to improve environmental safety factors (USEPA, 1999). The highest water quality occurred in Source water, with the exception of pH (Table 2). Appropriate treatment for alkalinity and pH in Source water would include acid injection and possibly reverse osmosis.

Sample Types other than the Source tended to have lower UV transmission, and high organic carbon, aerobic bacteria, and COD, and not all systems were managing microbial load. The greatest potential risk of clogged emitters in irrigation systems resulted from aerobic bacteria levels above 10,000 cfu/mL. Of the eight Locations with pretreatment bacterial counts above 10,000 cfu/mL (Table 4), treatment lowered bacteria counts below 10,000 cfu/mL in only half the Locations. Improvements to irrigation systems are required to reduce bacteria counts, including increased filtration to remove suspended particles and overall sanitizing demand, followed by more effective chemical treatment.

These results highlight that monitoring of biological, chemical, and physical water quality can be used to improve irrigation system design when implementing a water treatment technology. The density of aerobic bacteria can be counted to indicate the relative efficacy of a treatment technology to control microbes in greenhouse and nursery irrigation, particularly when providing chemical treatments or microemitter irrigation using recycled water. More detailed analysis of pretreatment and posttreatment for each Location should be conducted to determine if the treatment systems were effective or failed in control of aerobic bacteria, yeast, and mold.

This survey was not intended for comparison between treatment technologies because it was conducted at only one point in time. Installation of sampling ports before and after each treatment point should be a standard design feature to improve the ability to monitor irrigation quality. Regular monitoring of sanitizing agent levels and biological water quality may provide assessment of the water quality changes that are likely to occur over time and within a horticultural irrigation system. Before this survey, none of the Locations had measured physical water quality and pretreatment and posttreatment water quality variables such as aerobic bacteria counts, which are important monitoring variables to ensure correct operation of a treatment system. The results of this study provide a reference for irrigation quality and may be used as a guideline to develop and implement monitoring procedures to improve irrigation management.

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