Survey of Suspended Solids in Irrigation Water of Ornamental Plant Nurseries and Effects of Filtration

Jinsheng Huang, Ph.D.[1]; and Paul R. Fisher, Ph.D.[2]

Abstract: The objectives of this study are to (1) characterize the consistency of laser diffraction (LD) and automated dynamic image analysis (DIA) instruments in estimating the size of suspended peat particles in water and the sphericity of peat particles measured using DIA; (2) characterize the particle-size distribution of suspended solids in irrigation water sources from a survey of plant nurseries; and (3) analyze total suspended solids (TSS) upstream and downstream of fiber media and screen filters installed for filtration of recirculated water in commercial plant nurseries. Over 70% of peat particles had an estimated circularity value greater than 0.7, indicating a mix of elongated and spherical particles. The DIA and LD estimates of median particle diameter with circular particle-shape models yielded similar results when tested on three peat particle-size classes and two levels of TSS. TSS varied greatly in different water sources, with an average 3.3 ± 0.4 mg/L mean ± standard error, with a range of 2.5–4.5 mg/L for well water, average 4.7 ± 1.2 mg/L (range of 1.6–9.9 mg/L) from uncovered catchment basins, and an average of 40.0 ± 14.8 mg/L (range of 2.0–301.0 mg/L) from ebb-and-flood subirrigation return water, respectively. Across all water sources, TSS ranged from 1.6 to 301 mg/L, averaging 28 ± 10.4 mg/L. The suspended-particle diameter in the 10th, 50th (or median), and 90th percentiles by total particle volume was 28, 116, and 347 μm, respectively, which is relevant when considering the amount of suspended solids that are likely to be removed by filters of different micrometer sizes. Fiber media and screen filters reduced TSS by an average 57.9 ± 7.4% of the prefiltration TSS. Microscopy analysis of several fiber media filters showed that the pore sizes reported by vendors were smaller than the observed particle pore sizes. Multiple filtration stages would be ideal for ebb-and-flood water because of the high and variable TSS levels observed in recirculated ebb-and-flood water samples, the wide range of particle sizes and shapes, and the average removal of approximately half the TSS by a single stage of screen or fiber media filtration. **DOI: 10.1061/(ASCE)IR.1943-4774.0001391.**

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Introduction

Filtration to remove suspended particles can be a significant investment for greenhouse and nursery businesses, especially when irrigating with recirculated or surface water sources. Raudales et al. (2017) found capital costs as high as $47,000 for a particle filter in surveyed greenhouses, and operating costs of up to $0.78/1,000 L. Filtration is required to avoid clogging of irrigation lines and emitters with suspended particles, which results in nonuniformity of water distribution, plant losses from underwatering or overwatering, and increased runoff of water and fertilizer into the environment. Suspended particles can include sediment, sand, soil, container substrate components, chemical deposits, leaves, biofilm, algae, plant pathogens, and weeds. These particles increase turbidity (reducing the efficacy of ultraviolet radiation) and create a demand for active ingredients of oxidizers and biocides such as chlorine dioxide, hypochlorous acid, and copper, resulting in the need for particle filtration before use of a sanitation technology (Fisher et al. 2013). In addition, suspended solids can distribute pesticides and other contaminants adsorbed to particle surfaces (USEPA 2011).

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Total suspended solids (TSS) are defined as particles in water that are retained on a 2-μm filter (APHA 1998). The mechanisms of particle removal with filtration consist of straining, impaction, interception, adhesion, and flocculation (Levine et al. 1985). The removal mechanism of particulates in a filtration system is affected by particle size (Adin and Elimelech 1989). Large sand particles of 100–500 μm diameter can be removed by screens, discs, and centrifugal filters (Adin 1999; Yao et al. 1971). However, filters suitable for removal of small particles, for example microorganisms <10 μm, are either membrane filtration or slow sand filtration (Ehret et al. 2001; Stewart-Wade 2011; Ufer et al. 2008; Van Os 2010).

Particle characterization (particle size and shape) serves as an important tool toward understanding filter behavior and efficiency in order to design effective filtration systems for irrigation (Adin 1999). The size of suspended particles can be analyzed using laser diffraction (LD) or automated dynamic image analysis (DIA), and particle shape can also be measured using DIA (Tysmans et al. 2006; Xu 2000). Suspended particles that are likely to occur in recirculated greenhouse and nursery irrigation water include organic plant, microbial, and container substrate particles, and precipitates of fertilizer chemicals (such as Fe and P compounds). A previous survey found that greater than 50% of TSS in greenhouse and nursey irrigation water was composed of organic carbon materials (Meador et al. 2012). Suspended peat particles resulting from erosion from a natural peat bog have been analyzed using DIA (Baynes 2012). Because peat is a very common organic component in container substrates, quantifying peat particle sizes and shapes may assist growers in filter selection when irrigation runoff is captured for reapplication to the crop.

The objectives of this study are to (1) characterize the consistency of LD and DIA instruments in estimating the size of peat particles in water and the sphericity of peat particles measured using DIA; (2) characterize particle-size distribution of suspended solids in irrigation water sources from a survey of plant nurseries; and (3) analyze TSS upstream and downstream of fiber media and screen filters installed for filtration of recirculated water in commercial plant nurseries.

Experimentation on sieved peat for Objective 1 was necessary to confirm confidence in LD and DIA when these methods were subsequently used to evaluate irrigation samples for Objectives 2 and 3. The hypothesis was that the mean and median particle sizes estimated by the analytical instruments would fall within or be slightly above the tested screen size ranges of 44–74 μm, 75–149 μm, or 150–250 μm depending on size class, and that these estimates would be independent of TSS level. The expectation that the estimated spherical particle diameter may be greater than the sieve dimension was because in cases where particles are noncircular and slip through a sieve at their narrowest width, an estimated spherical particle diameter will be greater than the sieve opening (Tysmans et al. 2006).

Materials and Methods

Characterization of Peat Particle Size and Shape from Filtered Peat Samples

This experiment was run in order to evaluate Objective 1 by comparing sieved peat against particle-size estimates from LD and DIA methods. Solutions were prepared by filtering peat particles with metal screens (brass wire with square-section pores) (Fisher Scientific, Pittsburgh, PA) meeting current ASTM E11 (ASTM 2017) and ISO 3310-1 (ISO 2006) specifications, followed by evaluation of the size distribution and shape of these particles using two analytical instruments (laser diffraction and DIA). The purpose was to validate under controlled conditions that the size of peat particles estimated by the analytical equipment was similar between instruments and when compared with the screens. Particle shape (sphericity) was also evaluated using DIA because particle shape affects the efficacy of irrigation filters (Schalla and Waiters 1990).

Canadian sphagnum peat moss (SunShine Peat Moss, Sun Gro Horticulture Distribution, Bellevue, Washington) was thoroughly wetted with sufficient deionized water containing 600 mg/L of a surfactant (Psi-Matric, Aquatrols, Paulsboro, New Jersey) to more than saturate the substrate, filling all pores with water. Peat particles were left overnight to fully hydrate. Peat was then wet-sieved by passing through stacked screens of US 60 mesh (250 μm), US 100 mesh (149 μm), US 200 mesh (74 μm), and 325 US mesh (44 μm). Three size classes of peat particles were collected: coarse (passing through a 60 mesh screen but retained on a 100 mesh screen, 150 to 250 μm), medium (passing through a 100 mesh screen but retained on a 200 mesh screen, 75–149 μm), and fine particles (passing through a 200 mesh screen but retained on a 325 mesh screen, 45–74 μm). After drying at 70°C, either 5 or 50 mg of each particle class of dry peat was weighed and added back into 1 L of deionized water, resulting in two levels of suspended solids (5 or 50 mg/L) for each particle class. The peat particles were then hydrated a second time and mixed in the solution by placing the 1-L bottles on a rocker table for 1 h.

Peat suspended-solid solutions were analyzed for particle-size and volume distribution by the Research Service Centers of the Herbert Wertheim College of Engineering at the University of Florida with laser diffraction (LD) using a Beckman Coulter (Brea, California) LS 13 320 laser diffraction particle-size analyzer and with DIA using a Beckman Coulter RapidVUE particle shape and size analyzer. The LD instrument measured from 0.2 to 2,000 μm, and the DIA instrument can measure a particle-size range of 20–2,500 μm. In addition to the capability of the LD for measuring particle size, the DIA instrument can characterize particles in term of shape. The particle diameter determination intervals were 0–1,000 μm for the LD instrument and 20–1,000 μm for the DIA instrument.

Experimental treatments included factors of particle class (with three treatment levels of fine, medium, and coarse), and TSS levels (5 and 50 mg/L), with six replicate samples for each treatment in a factorial design. Analyzed variables included the estimated mean and median (50th percentile) particle diameter (μm) by total volume using a spherical model with LD, and the estimated median particle diameter using spherical and rectangular models with DIA. The DIA spherical model calculated the equivalent circular area diameter (ECAD), which is a commonly used diameter measure for noncircular shapes that estimates the diameter of a circle having the same area as the actual shape. The DIA rectangular or Feret width represents the smallest width of a particle. The DIA rectangular width may be useful for relating particle dimensions to sieve data because when particles are passed through a screen, coarser elongated particles can still slip through the openings if they are well-oriented (Tysmans et al. 2006).

Data were analyzed using ANOVA in SAS general linear models procedure (PROC GLM) version 9.4 software, and least-square mean values were calculated. Particle shape was analyzed using the sphericity parameter with DIA, which is a dimensionless number between 0 and 1 calculated on the basis of area (A) and perimeter (P). The sphericity parameter, C, more accurately termed circularity (Tysmans et al. 2006), is based on a two-dimensional image and uses the Cox (1927) circularity calculation, which equals 1 for a perfect circle and has been used to define the boundary irregularity of particles (Hentschel and Page 2003)

$$C = 4\pi A/P^2 \tag{1}$$

Frequency data of the number of particles from DIA in circularity value bins of 0.06–0.50, 0.51–0.60, 0.61–0.70, 0.71–0.80, 0.81–0.90, and 0.91–1.0 were analyzed for effects of peat particle-size class, TSS level, and their interaction using ANOVA with PROC GLM in SAS version 9.4.

Particle Size and Total Suspended Solids in Water Sources before Filtration in a Survey of Plant Nurseries

For Objective 2, to characterize particle-size distribution of suspended solids in irrigation water sources, irrigation water samples were collected before filtration at 11 greenhouse and nursery locations collaborating with universities in the Floriculture Research Alliance university/industry consortium in the United States (Floriculture Research Alliance 2019). Samples were taken during an active crop production period from May to June in 2011 and 2012. Multiple sites were sampled within some locations, resulting in 11 or 8 locations and 12 or 19 sampling sites in 2011 and 2012, respectively. The sites included Well, which was irrigation water that had not been stored or used for irrigation, Ebb-and-Flood water returning from subirrigation floors or benches, and Catchment Basin water from uncovered outdoor storage ponds sourced from rainfall and irrigation runoff water.

The surveyed greenhouses and nurseries produced both transplants and finished containerized ornamental crops. A detailed and

Table 1. Filter type and filter pore sizes used in the recirculated irrigation water system for locations surveyed during 2012

Business code	Site	Filter type	Water source	Reported filter pore size (μm)	Reported flow rate (L/min)
1	A	Screen, coarse	Ebb and flood (EF)	762	45
3	A	Screen, coarse	Ebb and flood (EF)	500	333
4	A	Screen, vibrating	Ebb and flood (EF)	100	852
4	B	Fiber media	Ebb and flood (EF)	88	852
6	A	Fiber media	Ebb and flood (EF)	52.5	2,839
6	B	Fiber media	Ebb and flood (EF)	17.5	2,839
6	C	Fiber media	Ebb and flood (EF)	10	2,839
7	B	Screen, coarse	Ebb and flood (EF)	1,000	303
8	C	Screen, rotary drum	Ebb and flood (EF)	89	189
8	D	Screen, rotary drum	Ebb and flood (EF)	89	189
9	A	Screen, vibrating	Ebb and flood (EF)	130	379
9	B	Fiber media	Ebb and flood (EF)	28	1,401
9	C	Screen, vibrating	Ebb and flood (EF)	88	757
11	B	Fiber media	Ebb and Flood (EF)	70	1,703

Note: Business code represents a specific location of a horticultural firm, and a Site is a water source within that location. Representative photographs of each filter class are shown in Fig. 1.

standardized sample collection and handling protocol including step-by-step photos was provided to each location for growers to follow. For each sampling site within a location, three replicate samples of water sources before filtration were taken on a single day while irrigation was occurring, with samples drawn from water running through pressurized irrigation lines. The volume per sample was 400 mL for 2011 and 1,000 mL for 2012, respectively. The three samples were packed in an insulated cloth cooler with an ice pack inside a polystyrene-insulated cardboard shipping box and sent back to the laboratory at the University of Florida on the day of collection by priority overnight courier.

The total suspended-solid concentration was immediately measured on a 200- or 400-mL sample in 2011 and 2012, respectively. Each sample was filtered with a Whatman (Maidstone, UK) 47-mm-diameter 934-AH 1.5-μm glass fiber filter and oven-dried at 105°C for 60 min to determine TSS. The effect of sample site on TSS data was analyzed using ANOVA in SAS PROC GLM, with separate analyses for each sample year because not all sample sites were evaluated both years.

A 150-mL subsample was used for particle-size analysis using the LD instrument. The 150-mL subsamples were first passed through a 1-mm mesh sieve to remove large particles before particle-size analysis. Particle-size parameters were calculated for the 10th (PC10), 50th (PC50), and 90th (PC90) percentile by total volume less than a given diameter. Parameter data were analyzed for effects of sampling site using ANOVA with PROC GLM in SAS separately by sample year.

Suspended-Solid Removal Efficiencies of Fiber Media and Screen Filters from a Survey of Plant Nurseries

For each of the eight locations and 14 sampling sites surveyed in 2012 that had either screen or fiber media filters (Table 1 and Fig. 1), three replicate pairs of 1-L samples were taken immediately upstream and downstream of filtration on a single day. The efficiency (E) of the filter at removing total suspended solids in these samples before and after filtration was calculated by dividing (TSS before filtration—TSS after filtration)/TSS before filtration. Data were analyzed using SAS PROC GLM with sampling site as the factor, with a $\log_{10}$ transformation because of a right-skewed distribution in TSS data.

Light Microscopy Photographs of Fiber Media

Because pore size was reported by grower participants but had not been independently verified, the pore size in four synthetic-fiber media filters from three plant nurseries was compared against a slide micrometer using light microscopy (Leica MZ16F fluorescence stereomicroscope, Meyer Instruments, Houston, Texas). The fiber media and a calibrating micrometer were digitally

(a) (b) (c) (d)

Fig. 1. Representative photographs of filter types evaluated in the greenhouse and nursery survey and detailed in Table 1: (a) coarse screen; (b) vibrating screen; (c) rotary drum screen; and (d) fiber media.

Table 2. ANOVA of the estimated arithmetic means or 50th percentile values for particle size measured using laser diffraction and automated dynamic image analysis with wet-screened peat in water at two suspended-solid levels (5 and 50 mg/L)

TSS (mg/L)	Screen (particle-size class description)	Metal screen width range (μm)	LD[a] diameter mean by volume (μm)	LD diameter median by volume (μm)	DIA[b] ECAD diameter 50th percentile by volume (μm)	DIA rectangle width 50th percentile by volume (μm)
5	Fine	45–74	93 ± 19	83 ± 10	92 ± 3	75 ± 3
5	Medium	75–149	163 ± 19	136 ± 10	149 ± 3	127 ± 3
5	Coarse	150–250	244 ± 19	210 ± 10	214 ± 3	178 ± 3
50	Fine	45–74	89 ± 19	80 ± 10	96 ± 3	78 ± 3
50	Medium	75–149	155 ± 19	138 ± 10	147 ± 3	119 ± 3
50	Coarse	150–250	279 ± 19	237 ± 10	234 ± 3	185 ± 3
Screen	—	—	$p \leq 0.001$	$p \leq 0.001$	$p \leq 0.001$	$p \leq 0.001$
TSS	—	—	NS[c]	$p \leq 0.001$	$p \leq 0.001$	NS
Screen × TSS interaction	—	—	$p \leq 0.01$	$p \leq 0.001$	$p \leq 0.001$	$p \leq 0.001$

Note: Values are least-square means ±95% confidence intervals at $\alpha = 0.05$. ECAD is the equivalent circular area diameter.
[a]LD was performed with a Beckman Coulter LS 13 320 laser diffraction particle-size analyzer.
[b]DIA was performed with a Beckman Coulter RapidVUE particle shape and size analyzer.
[c]NS = not significant at $p = 0.05$.

photographed under the light microscope. The length of the micrometer in pixels was then used to provide a micrometer scale for fiber media photographs and was visually compared with the pore size reported to growers by the fiber media vendors.

Results and Discussion

Characterization of Size and Shape Distributions of Peat Particles

Overall, there was high agreement of estimated diameters from the LD and DIA instruments, with the estimated median particle size with the DIA rectangular model having the greatest consistency with the mechanical screen size. The particle-volume distribution for screened peat measured with the LD and DIA instruments, and significance of main and interaction effects of screen size and TSS on estimated diameter from the ANOVA, are given in Table 2. The mean and 50th percentile values from LD, which assumed a circular particle profile, tended to be in the upper portion or above the mechanical screen diameter ranges. Mean values were greater than 50th percentile values (or medians), suggesting a right skew to the data where a few large particles had a relatively large contribution to the total particle volume. Although there was a significant interaction between screen size and TSS on the estimated mean and median diameter, there was no clear trend whereby increasing TSS resulted in a consistently higher or lower size estimate.

The DIA 50th percentile ECAD values, which assumed a circular particle profile, were also larger than or in the upper range of the mechanical screen diameter ranges. The DIA data were similar to the LD data, with a correlation coefficient r of 0.96 or higher. The rectangular DIA diameters, assuming a rectangular shape and with the width measurement provided in Table 2, were smaller than the circular data estimated from both the spherical DIA and LD models.

Differences between estimated particle diameter and the mechanical screen sizes include the effect of a circular model being used to estimate the diameter of noncircular particles (Tysmans et al. 2006), pliable particles squeezing through the screen at pressure, changes in particle size during sample processing, or adsorption of smaller particles following screening. Although there was a statistical effect of TSS, there was no more than 20% difference in estimated diameter from a given instrument at a particular screened particle size at the two TSS levels.

The results from this peat size and number test lend support for using either the LD or DIA instrument to analyze suspended particle size and evaluate filter performance in situations where peat is likely to be a significant contaminant in recirculated water.

The shape distribution of peat particles measured using DIA, along with representative values of the Cox (1927) circularity parameter [Eq. (1)] for different oval shapes as a reference, are shown in Fig. 2. The circularity parameter [Eq. (1)] has a value between 0 and 1, with 1 representing a perfect circle, determined from Eq. (1). Ovals at the top of the Fig. 2 are two-dimensional representations of different circularity values as a reference. Each data point was the mean of 36 replicates, including all peat screen sizes and concentrations from Experiment 1.

Within each sphericity value interval in Fig. 2, ANOVA results found no significant difference between peat particle classes, between two TSS levels, and the interaction between peat particle classes and TSS (data not shown). Sphericity data were therefore pooled together for the 36 replicate samples (Fig. 2).

Over 70% of the total number of particles had a circularity value greater than 0.7, indicating a mix of elongated and spherical particles, with the highest percent of particles in the 0.81–0.9 range (Fig. 2). Zielina (2011) found that particles with lower circularity were more likely to be removed during rapid sand filtration of particles (primarily silicate and aluminum oxide) from water compared with particles that were close to circular.

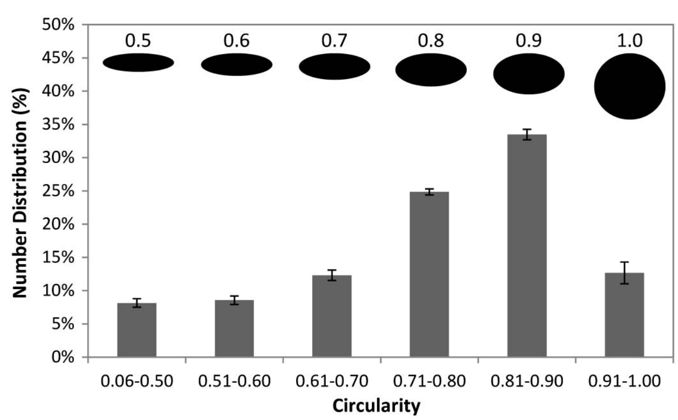

Fig. 2. Particle-shape distribution (circularity) of peat particles measured using DIA, by the mean percent of particle number. Error bar represents standard error with $n = 36$.

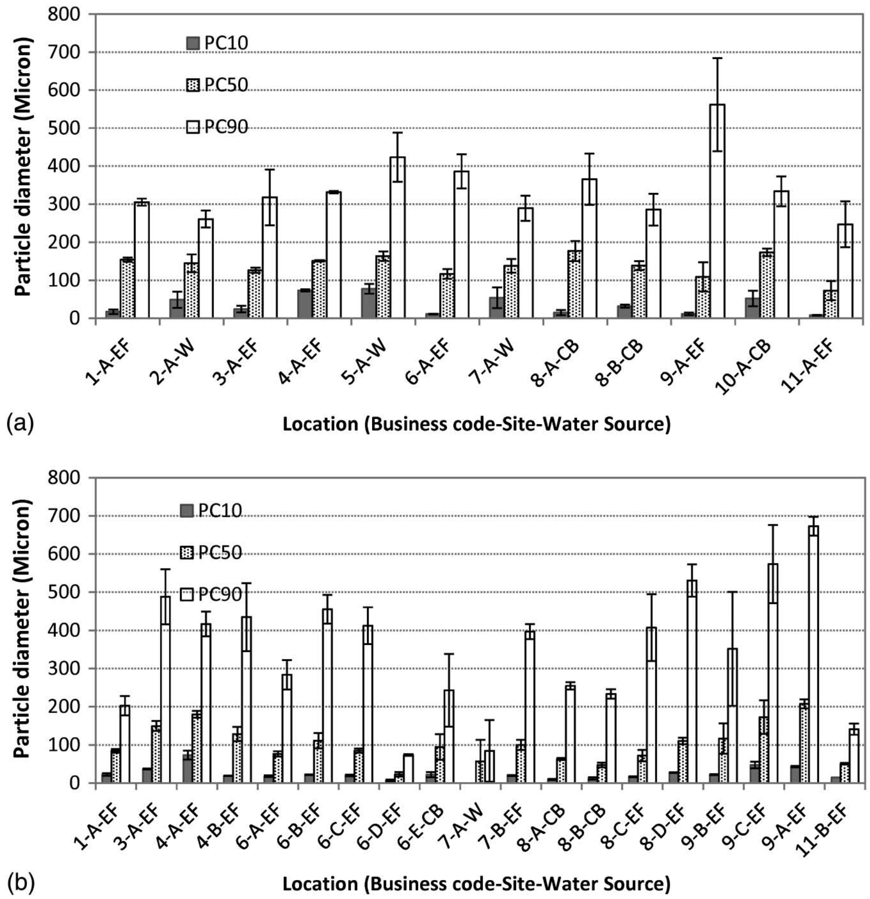

Fig. 3. Particle diameter estimated using laser diffraction at PC10, PC50, or PC90 by total particle volume in unfiltered irrigation systems at each location (business code-site-water source) in (a) 2011; and (b) 2012. Error bars represent the standard error with $n = 3$. Water sources included catchment basin (CB), ebb-and-flood (EF), and well (W).

Particle Size and Total Suspended Solids Analysis in the Survey of Plant Nurseries before Filtration

Particle-size distributions (Fig. 3) may help growers select the appropriate filter pore size for their filtration system for efficient removal of suspended solids in water. The 10th percentile (PC10, by volume) before filtration ranged from 8 to 78 μm with an average of 35 ± 7 μm (mean $\pm$ standard error) for the year 2011 [Fig. 3(a)], and 0.0 to 73 μm with an average of 24 ± 4 μm for the year 2012 [Fig. 3(b)], respectively. Therefore, a filter system removing 90% of particle volume would need to have the finest pore size in the filtration series smaller than 24 to 35 μm, particularly given the noncircularity of some particles shown in Fig. 2. The 50th percentile (PC50) before filtration ranged from 73 to 177 μm with an average of 139 ± 9 μm for the year 2011, and 23 to 207 μm with an average of 101 ± 11 μm for the year 2012, respectively. The 90th percentile (PC90) before filtration ranged from 247 to 562 μm with an average of 342 μm for the year 2011, and 73 to 673 μm with an average of 350 μm for the year 2012, respectively. Overall (combined data from 2011 and 2012), the average 10th, 50th, and 90th percentile value by volume was 28, 116, and 347 μm, respectively.

The PC90 data (representing the largest 10% of particle volume) for ebb-and-flood irrigation water in Figs. 3(a and b) averaged 380 ± 32 μm, indicating large particles that could be removed with a coarse prefilter with large pores (e.g., 250 μm). This would eliminate large particles returning from a subirrigation event at a rapid flow rate, thereby reducing clogging in a subsequent finer filter. Raudales et al. (2017) found that fiber media filters were generally more costly per unit of water volume treated compared with screen filters, which further supports the approach to prefilter water with a screen before finer filtration with a fiber media filter to reduce cost of the consumable fabric. The ideal filter arrangement for different water sources would also be affected by factors not analyzed in this study, for example the type of particles in different water sources (inorganic sediment in well water, algae in pond water, and container substrate in ebb-and-flood water), which means that different filter types (e.g., screen, sand media, disc, centrifugal sand separator, or fiber media) may be required depending on the local water quality. In addition, the type of irrigation system should be considered when selecting the final filtration step, with guidelines including a maximum 74-μm particle size for drip-irrigation emitters (Haman and Zazueta 2017). Combined with high water resistance from fine filtration pores, multiple filtration stages are likely to be required to remove TSS and result in an acceptable particle-size distribution for microirrigation.

Measured TSS before filtration varied from 1.6 to 119 mg/L, with an average value of 14 ± 10 mg/L in 2011 [Fig. 4(a)]. The TSS value for the sampling year 2012 ranged from 2 to 301 mg/L, with a mean of 37 ± 16 mg/L [Fig. 4(b)]. Overall, the average TSS from the samples over the 2-year period was 28.4 ± 10.4 mg/L. Well water and catchment basins had the lowest TSS, with average values of 3.3 ± 0.4 and 4.7 ± 1.2 mg/L, respectively. Ebb-and-flood water sources had the highest and most variable TSS, averaging 40.0 ± 14.8 mg/L, which illustrates that high variability in suspended particles is likely in recirculated systems.

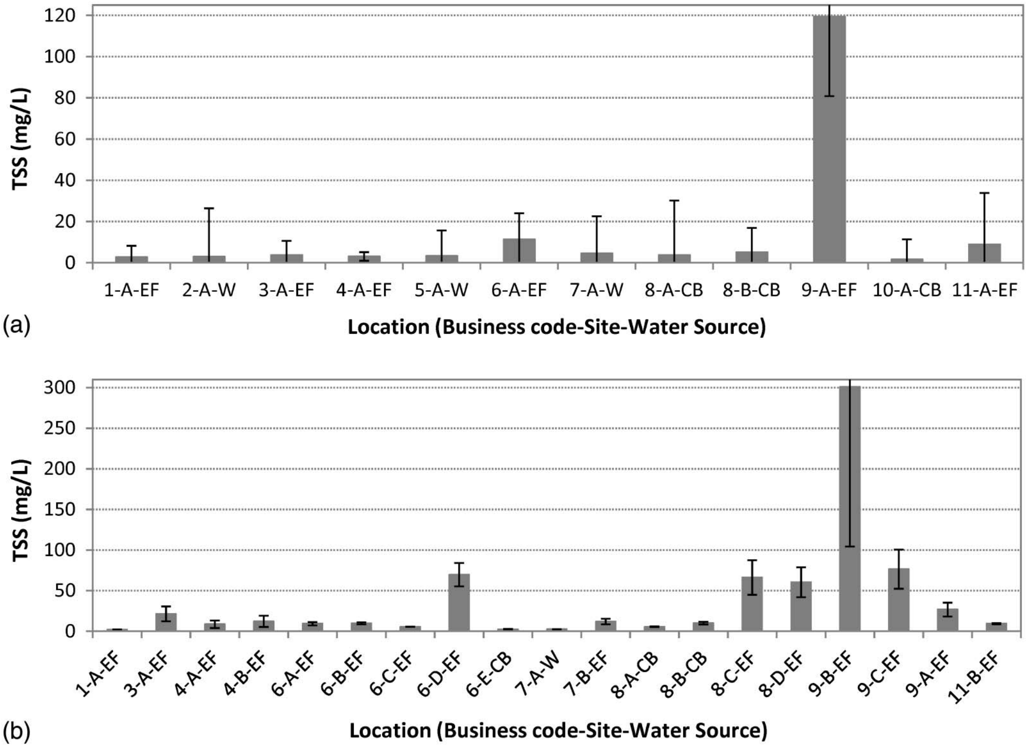

Fig. 4. Total suspended solids in irrigation systems before filtration in plant nursery locations (business code-site-water source) in (a) 2011; and (b) 2012. Error bars represent standard error with $n = 3$. Water sources included catchment basin (CB), ebb-and-flood (EF), and well (W). The y-axis is truncated for clarity.

There are various interpretations of acceptable TSS levels for different irrigation purposes. For sprinkler irrigation with reclaimed water (partially treated municipal wastewater), TSS less than 30 mg/L may be necessary to avoid clogging of sprinkler heads (USEPA 2012). Bucks et al. (1979) considered that clogging potential for drip-irrigation systems increased from zero risk below 10 mg/L TSS to a high risk at over 160 mg/L, and many university extension bulletins use a threshold of 100 mg/L TSS as a severe clogging risk for drip irrigation (e.g., Storley 2004). Suspended particles can impact irrigation water sanitation, and 5 mg/L TSS is a general recommendation prior to disinfection to ensure reliable destruction of pathogenic microorganisms in reclaimed water (USEPA 2012). Fisher et al. (2013) found that 50 mg/L TSS from fine peat particles resulted in a chlorine demand of approximately 0.5 mg/L after 2 min of exposure time. One location in 2011 and five locations in 2012 (Fig. 4) had TSS levels in ebb-and-flood water greater than 50 mg/L, indicating potential to impact water sanitation or clogging of irrigation lines.

Suspended-Solid Removal Efficiencies of Fiber Media and Screen Filters

The suspended-solid removal efficiencies (Fig. 5) of fiber media and screen type filters were analyzed for the year 2012 samples. There were significant main effects of sampling site and prefiltration versus postfiltration ($p < 0.0001$) but no interaction. The average prefiltration and postfiltration TSS were 44.3 ± 17.0 and 18.4 ± 5.3 mg/L, respectively, and the average percent reduction in TSS by filtration was $57.9 \pm 7.4\%$ of the prefilter values. Filter efficiency is likely to be influenced by many factors, such as filter type, filter pore size, flow rate, and type of particles. Reported screen filter pore sizes varied from 88 to 1,000 μm, with a median value of 100 μm (Table 1).

Light Microscopy of Fiber Media

To further evaluate the fiber media filter pore sizes, four fiber media samples were analyzed for pore sizes using light microscopy photographs technology (Fig. 6), where the length of a micrometer in pixels was used to generate the 1-mm scale added to the fiber media photographs. Figs. 6(a and b) show findings using surface filters

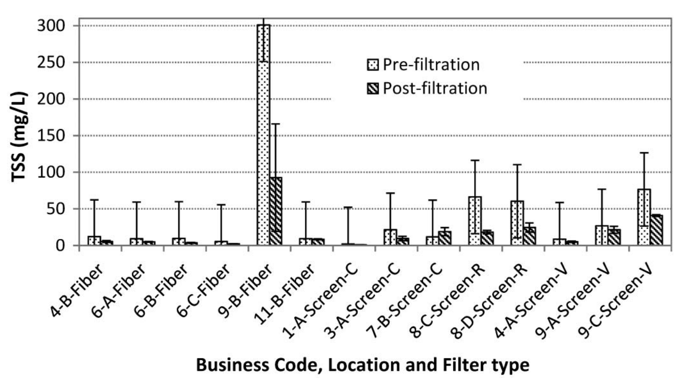

Fig. 5. Total suspended solids before and after filtration with fiber media and screen filtration systems for recirculated water sampled in 2012 (Table 1 gives filter details). Labels indicate location, sampling site, and filter type. Filter types included fiber media, cascade screen (Screen-C), rotary screen (Screen-R), and vibrating screen (Screen-V) as shown in Fig. 1. Error bars represent the standard error with $n = 3$. The y-axis is truncated for clarity.

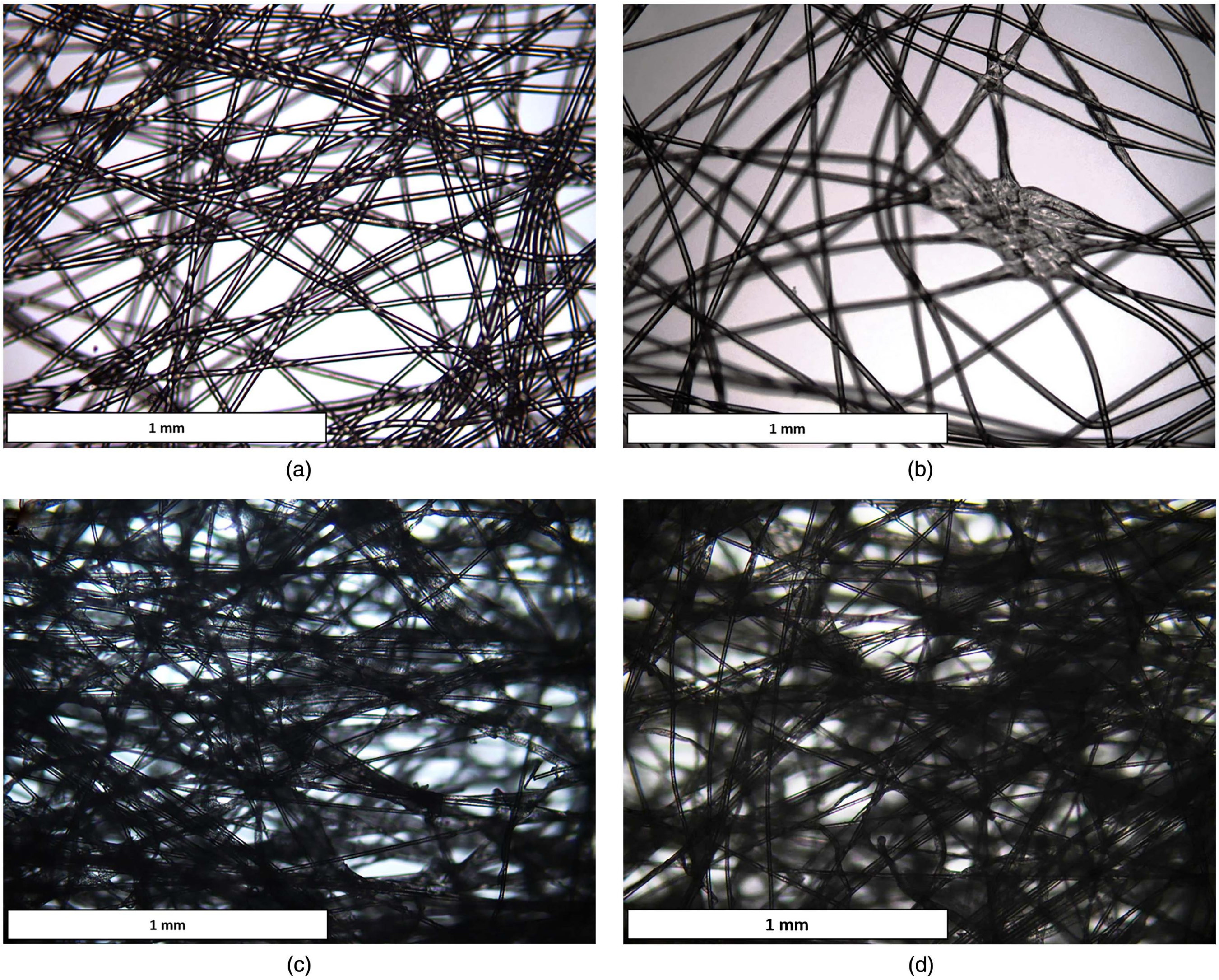

Fig. 6. Digital light microscope photographs of four fiber media fabrics. The pore size described to grower participants by filter vendors were (a) approximately 80% efficient at 50 μm; (b) 50–60 μm; (c) 28 μm; and (d) 18 μm.

that capture most particles in the top layer of fabric, whereas Figs. 6(c and d) show findings using depth filters, where particles also become embedded within multiple fabric layers. The measured pore sizes were significantly larger than the pore sizes claimed by the manufacturer. For example, a fiber media that reportedly had a 50-μm pore size had much larger measured pore sizes ranging up to 500 μm. In follow-up discussion with fiber media suppliers, the reported pore size was evidently a nominal value based on resistance to airflow. In addition, effective pore size changes in multilayered depth media as particles become embedded in the fibers. Growers should therefore take this discrepancy into account when interpreting pore size of fiber media for use with irrigation water.

Conclusions

Particle-size analysis using either LD or DIA can be used to characterize particle sizes in recirculated water and evaluate the filter pore size required for reducing suspended solids. Based on DIA, peat particles included both elongated and spherical shapes. Particle-volume distribution can be used to determine whether the particles larger than the filter pores were presented in TSS. Overall, the average 10th, 50th (or median), and 90th percentile value by volume was 28, 116, and 347 μm, respectively. The TSS in water ranged from 1.6 up to 301 mg/L, averaging 28.4 ± 10.4 mg/L across all water sources. Water sources differed in TSS, with an average 3.3 ± 0.4 mg/L for well water, 4.7 ± 1.2 mg/L for catchment basin water, and 40.0 ± 14.8 mg/L for the ebb-and-flood water, respectively.

Results showed that the effective pore size in fiber media for irrigation water filtration was larger than that reported by vendors. If filtration is used to treat water before distribution through fine irrigation emitters or as an initial step to remove chlorine demand for control of pathogens, more than one filtration stage may be required for ebb-and-flood recirculated water samples. This conclusion is based on the high and variable observed TSS level, the wide range in particle sizes and shapes, and an average 57.9% removal of particles by each stage of screen or fiber media filtration.

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