Nitrogen Rate, Irrigation Frequency, and Container Type Affect Plant Growth and Nutrient Uptake of Encore Azalea ‘Chiffon’

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Abstract. One-year-old liners of Encore® azalea ‘Chiffon’ (*Rhododendron* sp.) were transplanted in Apr. 2013 into two types of one-gallon containers: black plastic container and paper biodegradable container. Azalea plants were fertilized with 250 mL of nitrogen (N) free fertilizer solution twice weekly plus N rate of 0, 5, 10, 15, or 20 mm from ammonium nitrate (NH₄NO₃). All plants were irrigated with the same total volume of water through one or two irrigations daily. Plant growth and N uptake in response to N fertilization, irrigation frequency, and container type were investigated. The feasibility of biodegradable paper containers was evaluated in 1-year production of Encore® azalea ‘Chiffon’. Paper biocontainers resulted in increased plant growth index (PGI), dry weights (leaf, stem, root, and total plant dry weight), leaf area, and root growth (root length and surface area) compared with plastic containers using N rates from 10 to 20 mm. Biocontainer-grown plant had more than twice of root length and surface area as plastic container-grown plant. Leaf SPAD reading increased with increasing N rate from 0 to 20 mm. One irrigation per day resulted in greater PGI, root dry weight, root length, root surface area, and root N content than two irrigations per day. Higher tissue N concentration was found in plants grown in plastic containers compared with those grown in biocontainers when fertilized with 15 or 20 mm N. However, N content was greater for plants grown in biocontainers, resulting from greater plant dry weight. The combinations of plastic container and one irrigation per day and that of 20 mm N and one irrigation per day resulted in best flower production, 21.9 and 32.2 flowers per plant, respectively. Biocontainers resulted in superior vegetative growth of azalea plant compared with plastic containers with sufficient N supply of 10, 15, and 20 mm.

Azaleas are generally known as light feeders, requiring low levels of N fertilization in production (Larson, 1993). They do not respond well to high N rates, which can

increase plant susceptibility to fungal disease and reduce winter hardiness (Witt, 1994). According to Michałojć and Koter (2012), the optimal nutrient levels in azalea leaves are 1.88% to 2.20% N, 1.0% to 1.7% potassium (K), and 0.60% to 1.20% calcium (Ca). Under overhead irrigation, increasing N rate from 1.0 to 1.5 or 2.0 lb N/yard³ resulted in lower shoot dry weight and shoot height of *Rhododendron* sp. ‘George Tabor’, and 1.5 lb N/yard³ was recommended for resin-coated controlled-release fertilizer (Nutricote 17N–3.1P–6.7K, 180 d at 77 °F) (Million et al., 2007). In another study, increasing N fertilization rate was found to promote shoot growth of *Rhododendron* ‘Karen’, with decreasing N and phosphorus (P) fertilization rates promoting root growth (Ristvey et al., 2007). Optimal plant growth was maintained using an intermediate fertilization rate (100 mg N and 5 mg P per week) compared

with lower (25 mg N) or higher (250 mg N) fertilization rates. Increasing fertilization rates (N and P) increased the amount of nutrient leached to the environment and decreased uptake efficiency (Ristvey et al., 2007). Bi et al. (2007) reported similar results where N uptake efficiency of 1-year-old rhododendron (*Rhododendron* ‘P.J.M.’) and azalea (*Rhododendron* ‘Cannon’s Double’) declined linearly with an increasing rate of N fertilization from 5 to 20 mm. The investigation of the nutrient requirements of a specific species is important for optimizing nutrient management and reducing environmental contamination. Optimum nutrient applications for a species are often only valid under a certain set of growing conditions, resulting in certain nutrient availability in the substrate to plant root systems (Bi et al., 2007; Million et al., 2007; Ristvey et al., 2007). Given sufficient N supply, N uptake was considered to be subject to a plant’s internal regulation depending on growth rate (Gastal and Lemaire, 2002). Therefore, determination of optimum N rate should be based on both substrate availability of the nutrient (N supply) and crop growth (N demand).

Fertilizer application rates are commonly determined in nursery production based on the assumption that water availability does not limit nutrient uptake and that container capacity should be maintained to promote plant growth and nutrient uptake (Beeson, 1992; Scagel et al., 2011). However, it may be impractical to maintain container capacity in production. Nutrient availability has been shown to decline with low soil water content, which becomes a limiting factor for nutrients to become soluble and be delivered to root surface (Marschner, 2012). Nutrient uptake can be further decreased when a dry substrate has impaired root growth, especially in a dry climate (Marschner, 2012). Because soil moisture conditions can be altered by altering irrigation frequency (Levin et al., 1980), the influence of irrigation frequency on plant growth and nutrient uptake has been investigated. Neilsen et al. (1995) reported that high irrigation frequency improved tree growth of ‘Gala’ apple (*Malus domestica*) than low irrigation frequency, with less effect on leaf nutrient concentration. Canopy volume, trunk cross-sectional area, dry weight, shoot length, leaf area, and total root dry weight of young ‘Hamlin’ orange (*Citrus sinensis*) trees were significantly reduced by low irrigation frequency (Marler and Davies, 1990). Increased irrigation frequency was found to reduce N leachate more than continuous irrigation using the same total irrigation quantity (Fare et al., 1994).

Traditionally, when plants are grown in plastic containers, evaporative loss of water is mainly through the substrate surface rather than the container sidewall because plastic containers are impervious to water. Use of biodegradable containers as a sustainable alternative to plastic containers can alter water consumption characteristics of container-grown plants (Koeser et al., 2013a; Wang et al., 2015). Biocontainers

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constructed with materials such as peat, wood fiber, straw, or paper are highly porous and tend to require more frequent irrigation and a higher total amount of water than traditional plastic containers (Evans et al., 2010; Koeser et al., 2013a; Wang et al., 2015). With increasing water loss between irrigation events, some biocontainers produced smaller plants of 'Yellow Madness' petunia (*Petunia ×hybrida*) (Koeser et al., 2013a). However, sidewall water loss from biocontainers was reported to reduce substrate temperature, which helped alleviate heat stress and enhanced plant survival at locations with hot summer conditions (Nambuthiri et al., 2015).

Growth response of Encore® azaleas under different N fertilization levels and irrigation frequencies when grown in biocontainers compared with plastic containers has not been determined. Considering the container used to grow nursery plants may have considerable influence on plant water consumption characteristics, container choice may alter the irrigation requirement and nutrient uptake of a given species. Therefore, the objectives of this study were to 1) investigate the influence of increased irrigation frequency on growth and N uptake of Encore® azalea 'Chiffon', 2) compare growth response of plants grown in a black plastic container with a biocontainer made from recycled paper, and 3) determine the optimum N fertilization rate based on irrigation frequency and container type. Results of this study will provide valuable reference for the fertilization and irrigation requirements of Encore® azalea 'Chiffon', a dwarf, slow-growing cultivar.

Materials and Methods

Plant culture and treatments. The study was conducted at Mississippi State University (lat. 33°26' N, long. 88°47' W, USDA hardiness zone 8a) in 2013. One-year-old liners (grown in 4-inch trays) of Encore® azalea 'Chiffon' were potted in pine bark substrate (100% adjusted with 1 lb/yard lime; ≈1.5 cm particle size) into two types of 1-gallon containers. One is a black plastic container (GL 400; top diameter 17.78 cm, bottom diameter 18.10 cm, volume 3.785 L; Nursery Supplies® Inc., Chambersburg, PA) and the other is a biodegradable container (biocontainer) made from a mix of recycled paper (7 × 7 RD; interior top diameter 18.7 cm, bottom diameter 14.9 cm, height 17.1 cm, and volume 3.90 L; Western Pulp Products Co., Corvallis, OR). All plants were maintained outdoors in full sun. Each azalea plant was fertilized with 250 mL of N-free fertilizer (Cornell No. N Eq. 0–6–27; Green-Care Fertilizers, Kankakee, IL) plus 0, 5, 10, 15, or 20 mm N from NH₄NO₃ twice weekly from 23 Apr. to 15 Sept. 2013. Plants were irrigated either once per day at 8:00 AM or twice per day at 8:00 AM and 2:30 PM with the same total daily irrigation amount. Plants were irrigated to replace daily water loss plus 15% leaching fraction.

Measurements and data collection. Plant height and widths (width 1, the greatest width; width 2, perpendicular to width 1) were measured on each plant every 2 weeks. Plant growth index was calculated as the average of plant height, width 1, and width 2. Three fully expanded new leaves were selected from each plant to measure their leaf SPAD reading using a chlorophyll meter (SPAD 502 Plus; Konica Minolta, Tokyo, Japan) on the same interval as plant height and widths. An average of the three readings from three leaves were calculated to represent SPAD of a specific plant. Using plants irrigated once per day, daily water use (DWU) was estimated using a gravimetric method by subtracting pot weight 24 h after irrigation from the weight of the container at container capacity (roughly 30 min after irrigation). DWU was measured on three dates during the growing season: 30 Aug., 25 Sept., and 21 Oct. 2013. Flower number produced per plant was recorded from the opening of the first flower to the time of destructive harvest in November.

Plants were destructively harvested and separated into root, stem, and leaf structures on 12 Nov. 2013, 32 weeks after transplanting. Leaf area of each plant was recorded at harvest using a leaf area meter (LI-3100C; LI-COR Inc., Lincoln, NE). Roots of three freshly harvested plants from each treatment combination were washed free of substrate and scanned for an image (EPSON® Expression 10000XL; Epson America, Inc., Long Beach, CA). Root length and surface area were measured by analyzing the root image using WinRHIZO software (Regent Instruments Inc., Québec, Canada).

Dry weights and N analyses. All plant samples were cleaned free of debris and substrate using deionized water and oven dried at 60 °C to a constant dry weight. Dry weight of each sample was recorded. Total plant dry weight was calculated by summing dry weight of each structure (leaf, stem, and root) for each plant. Each sample was then ground to pass a 1-mm sieve using a Wiley mill for nutrient analyses. The Kjeldahl procedure, where organic N is converted into NH₄-N, a form that can be analyzed by a variety of techniques, was used for the determination of total N concentration using 0.1 g of dry tissue sample (Bremner, 1965). N content in each structure was estimated by multiplying N concentration with dry weight of a specific structure. Total plant N content was calculated by summing N content in leaf, stem, and root. Average plant N concentration was calculated by dividing total plant dry weight by total plant N content.

Experimental design and data analyses. The treatment design was a complete factorial design with N rate (five rates), irrigation frequency (two frequencies), and container type (two types) as three experimental factors, providing 20 treatment combinations. The experimental design was a completely randomized design. Five single-plant replications were used per treatment combination. Significance of main effects or the interaction

among factors was determined by analysis of variance (ANOVA) using the GLM procedure of SAS (9.4; SAS Institute, Cary, NC). Where indicated by ANOVA, means were separated by Fisher's least significant difference test at $P < 0.05$.

Results

The interaction between N rate and container type was significant in affecting most response variables in this study, including PGI ($P < 0.0001$), dry weights ($P < 0.0001$), leaf area ($P < 0.0001$), root length ($P < 0.0001$), root surface area ($P < 0.0001$), DWU ($P = 0.0019$ on 30 Aug. and $P = 0.036$ on 21 Oct.), and tissue N concentration and content (Fig. 1; Tables 1 and 2). The main effect of irrigation frequency was significant on PGI, root dry weight, root length, root surface area, and root N content (Table 3). Except for flower production, irrigation frequency did not interact with N rate or container type on other response variables (Fig. 2).

Plant growth. Growth of azalea transplants were uniform starting from 2 weeks after transplanting, with no significant difference in PGI or SPAD readings among all treatment combinations (data not shown). By the time of destructive harvest in November, SPAD reading was affected by the main effect of N rate ($P < 0.0001$) and increased significantly with increasing N rate (from 17.0 at 0 mm to 38.6 at 20 mm N), irrespective of irrigation frequency or container type (Table 1). PGI was affected by irrigation frequency ($P = 0.0107$) and the interaction between N rate and container type ($P < 0.0001$) (Tables 1 and 3). Plants irrigated once per day had 7.7% higher PGI (18.56) than those irrigated twice per day (17.35) averaged over all N rates and both container types (Table 3). Plants fertilized with 10–20 mm N generally had higher PGI than those fertilized with 0 or 5 mm N in plastic or biocontainers. However, growing trend in plastic containers is different from that in biocontainers. When grown in plastic containers, PGI of azalea plant increased significantly (from 12.07 to 19.27) with increasing N rates from 0 to 10 mm. Plastic containers resulted in similar PGI when plants were fertilized with higher N rates, 19.27, 17.93, and 17.70 with 10, 15, and 20 mm N, respectively. When grown in biocontainers, PGI of azalea plant increased significantly (from 11.13 to 24.33) with increasing N rates from 0 to 15 mm. Biocontainers resulted in similar PGI when plants were fertilized with 15 or 20 mm N. Besides, biocontainers resulted in higher PGI than plastic containers at higher N rates, 13.8%, 35.7%, and 30.0% higher at 10, 15, and 20 mm N, respectively.

Dry weights (leaf, stem, root, or total plant dry weight) exhibited a similar trend as with PGI, which were affected by the interaction of N rate and container type (Table 1). Irrigation frequency affected root dry weight, but not dry weight of leaf, stem, or total plant,

Fig. 1. Daily water use measured on 30 Aug. (A), 25 Sept. (B), and 21 Oct. (C), 2013. Encore® azalea ‘Chiffon’ plants were fertilized with 0, 5, 10, 15, or 20 mM nitrogen from ammonium nitrate and grown in plastic containers or paper biocontainers. Different lower case letters on top of each bar suggest significant difference compared by Fisher’s protected least significant difference procedure at $P < 0.05$.

Table 1. Plant growth index (PGI), SPAD, dry weights, leaf area, and root growth of Encore® azalea ‘Chiffon’ plants.

N rate (mm) ^z	Container	SPAD	PGI	TDW (g) ^y	RDW (g)	SDW (g)	LDW (g)	Leaf area (cm ²)	Root length (cm)	Root surface area (cm ²)
0	Biocontainer	17.0 e	11.13 f	3.59 e	1.78 e	1.36 d	0.45 f	43 e	3,601 de	185 ef
	Plastic		12.07 f	3.80 e	1.55 e	1.59 d	0.66 f	54 e	3,161 e	166 f
5	Biocontainer	24.8 d	14.87 e	7.77 d	3.20 d	2.22 cd	2.35 e	199 d	5,697 c	363 c
	Plastic		16.43 de	8.83 d	3.23 d	2.62 c	2.98 de	259 d	4,603 de	300 cd
10	Biocontainer	32.7 c	21.93 b	18.10 b	6.79 b	4.90 b	6.43 b	553 b	9,805 ab	775 b
	Plastic		19.27 c	13.66 c	4.72 c	4.10 b	4.84 c	408 c	4,462 cd	313 cd
15	Biocontainer	35.7 b	24.33 a	24.61 a	8.64 a	6.58 a	9.39 a	849 a	10,668 a	910 a
	Plastic		17.93 cd	14.56 c	4.23 cd	4.81 b	5.53 bc	511 bc	3,962 de	283 cde
20	Biocontainer	38.6 a	23.90 ab	25.81 a	8.38 a	7.54 a	9.89 a	944 a	8,774 b	726 b
	Plastic		17.70 cd	12.06 c	3.53 d	4.27 b	4.26 cd	400 c	3,160 e	245 def
Irrigation effect ^x	P value	0.7391	0.0107	0.134	0.0443	0.3864	0.2295	0.1497	0.0017	0.0473
N effect	P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Container effect	P value	0.7938	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
N*Container	P value	0.8602	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^zEncore® azalea ‘Chiffon’ plants were fertilized with 0, 5, 10, 15, or 20 mm nitrogen (N) from ammonium nitrate, grown in plastic containers or paper biocontainers, and irrigated once or twice per day with the same total daily irrigation volume. Responses were influenced by the main effect of N rate, irrigation frequency, or the interaction between N rate and container type.

^yTDW stands for total plant dry weight, estimated by summing dry weights of leaf, stem, and root of a given plant; RDW stands for root dry weight; SDW stands for stem dry weight; LDW stands for leaf dry weight.

^xA P value < 0.05 suggests significant difference caused by either the main effect of a certain factor or the interaction between N rate and container type determined by analysis of variance. Different lower case letters within a column suggest significant difference compared by Fisher’s protected least significant difference procedure.

with azalea plants irrigated once per day having 11.7% higher root dry weight than those irrigated twice per day (Table 3). Trend of dry weight in each container type was also similar with that of PGI in plastic or

biocontainers. Plants fertilized with 10–20 mM N generally had higher dry weight (leaf, stem, root, or total plant) than those fertilized with 0 or 5 mM N (Table 1). Using each N rate from 10 to 20 mM, plants grown in

biocontainers had higher dry weight (leaf, stem, root, or total plant) than those grown in plastic containers, except the similar stem dry weight between container types at 10 mM N. Biocontainers resulted in total plant dry

Table 2. Tissue nitrogen (N) concentration and N content of Encore® azalea ‘Chiffon’ plants.

N rate ^z	Container	N concn (%)				N content (mg)			
		Leaf	Stem	Root	Avg ^y	Leaf	Stem	Root	Total ^x
0	Biocontainer	0.83 ed	0.45 f	0.39 ef	0.47 f	3.63 f	6.1 e	6.9 f	16.6 f
	Plastic	0.75 e	0.45 f	0.36 f	0.47 f	5.01 f	7.4 e	5.6 f	18.0 f
5	Biocontainer	0.89 d	0.58 e	0.40 ef	0.92 b	20.5 ef	12.8 de	12.7 de	46.0 e
	Plastic	0.89 d	0.60 de	0.43 de	1.01 a	26.8 e	15.9 d	13.7 d	56.4 e
10	Biocontainer	1.00 c	0.59 e	0.43 de	0.60 e	64.5 cd	28.4 c	29.4 b	122.3 cd
	Plastic	1.05 c	0.71 c	0.47 cd	0.64 de	50.6 d	28.9 c	21.9 c	101.4 d
15	Biocontainer	1.09 c	0.67 cd	0.51 bc	0.68 d	101.9 b	44.0 b	43.3 a	189.2 b
	Plastic	1.29 b	0.83 b	0.59 a	0.75 c	70.6 c	39.3 b	25.2 bc	135.1 c
20	Biocontainer	1.33 b	0.82 b	0.52 b	0.77 c	132 a	61.4 a	43.8 a	237.2 a
	Plastic	1.44 a	0.96 a	0.59 a	0.93 b	60.2 cd	40.1 b	20.5 c	120.7 cd
Irrigation effect ^w	<i>P</i> value	0.5303	0.1839	0.171	0.6783	0.1599	0.8809	0.0086	0.1324
N effect	<i>P</i> value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Container effect	<i>P</i> value	0.0089	<0.0001	0.0006	<0.0001	<0.0001	0.0152	<0.0001	<0.0001
N*container	<i>P</i> value	0.0019	0.0172	0.0194	0.0004	<0.0001	<0.0001	<0.0001	<0.0001

^zEncore® azalea ‘Chiffon’ plants were fertilized with 0, 5, 10, 15, or 20 mM N from ammonium nitrate, grown in plastic containers or paper biocontainers, and irrigated once or twice per day with the same total daily irrigation volume. Responses were affected by the interaction between the N rate and container type and the main effect of irrigation frequency on root N content.

^yAverage N concentration in a plant was determined by dividing total N content by total plant dry weight in a given plant.

^xTotal plant N content was estimated by summing N content in leaf, stem, and root of a given plant.

^wA *P* value <0.05 suggests significant difference caused by either main effect of a certain factor or the interaction between N rate and container type determined by analysis of variance. Different lower case letters within a column suggest significant difference compared by Fisher’s protected least significant difference procedure.

Table 3. Effect of irrigation frequency on plant growth index (PGI) and root growth of Encore® azalea ‘Chiffon’.

Irrigation per day ^z	PGI ^y	Root dry wt (g)	Root length (cm)	Root surface area (cm ²)	Root nitrogen content (mg)
Once	18.56 a	4.86 a	6,260 a	451.4 a	24.1 a
Twice	17.35 b	4.35 b	5,319 b	401.9 b	20.5 b

^zEncore® azalea ‘Chiffon’ plants were irrigated once or twice per day with the same total daily water volume.

^yDifferent lower case letters within a column suggest significant difference indicated by Fisher’s protected least significant difference procedure with a *P* value <0.05.

Fig. 2. Flower number per plant affected by the interaction between nitrogen (N) rate and irrigation frequency (A) as well as the interaction between container type and irrigation frequency (B). Encore® azalea ‘Chiffon’ plants were fertilized with 0, 5, 10, 15, or 20 mM N from ammonium nitrate, grown in plastic containers or paper biocontainers, and irrigated once or twice per day with the same total daily water volume. Different lower case letters on top of each bar suggest significant difference among treatment combinations compared by Fisher’s protected least significant difference procedure at *P* < 0.05.

weight of 18.10, 24.61, and 25.81 g at N rates of 10, 15, and 20 mM, respectively. Compared with biocontainers, plastic containers resulted in total plant dry weight of 13.66, 14.56, and 12.06 g, and 27.4%, 40.8%, and 53.3% lower than biocontainer-grown plants at 10, 15, and 20 mM N, respectively.

Besides root dry weight, root length and root surface area were affected by the main effect of irrigation frequency and the interaction between N rate and container type (Table 1). One irrigation per day resulted in a root length of

6260 cm and a root surface area of 451.4 cm², 17.7% and 12.3% higher, respectively, compared with 5319 cm and 401.9 cm² with two irrigations per day (Table 3). There was no significant difference in root length at 0 mM N, or root surface area at 0 or 5 mM N between container types (Table 1). By comparison, using any N rate from 10 to 20 mM, greater root length and root surface area were found when the plant was grown in biocontainers than in plastic containers, with biocontainer-grown plants having

more than twice the root growth of plastic container-grown plant. When grown in biocontainers, plants fertilized with higher N rates from 10 to 20 mM had greater root length and root surface area than those with no N or 5 mM N. However, root growth of plants grown in plastic containers was unaffected as much by N rate as in biocontainers. In plastic containers, root length and root surface area were comparable at 5, 10, and 15 mM N, greater than those at 0 or 20 mM N.

Leaf area. Leaf area was also affected by the interaction between N rate and container type, not by irrigation frequency, sharing similar trend with PGI and dry weights (Table 1). Regardless of container type, higher N rates from 10 to 20 mM resulted in greater leaf area than did 0 and 5 mM N. There was no significant difference in leaf area between container types at 0 or 5 mM N (Table 1). Plastic containers resulted in no difference in leaf area when plants were fertilized with 10, 15, or 20 mM N. However in biocontainers, increasing N rate from 0 to 15 mM resulted in increasing leaf area (43, 199, 553, and 849 cm² at N rate from 0 to 15 mM) with no difference in leaf area between N rates of 15 and 20 mM (944 cm²). At each N rate from 10 to 20 mM, biocontainers produced plants with 35.5%, 66.1%, and 136% greater leaf area than did plastic containers, respectively.

Flowering performance. Flower number per plant was affected by the interactions between irrigation frequency and N rate ($P = 0.0153$) (Fig. 2A) and that between irrigation frequency and container type ($P = 0.0179$) (Fig. 2B). Generally, no N treatment resulted in fewer than five flowers per plant throughout the growing season, with flower number per plant increasing to 13.2 (one irrigation per day) and 11.6 (two irrigations per day) using 5 mM N (Fig. 2A). Using N rate of 10 and 20 mM, one irrigation per day resulted in comparable highest flower number of 26.4 and 32.2 flowers per plant, 66.0% and 85.1% higher, respectively, than plant irrigated twice per day at each N rate. There was no difference in flower number per plant between two irrigation frequencies using 15 mM N, where flower number was 22.8 per plant with one irrigation and 23.4 per plant with two irrigations per day. Under the interaction between irrigation frequency and container type, azalea plants grown in plastic containers and irrigated once per day produced the greatest number of flowers (21.9 per plant), greater than those grown in biocontainers (17.0 per plant when irrigated once or 15.6 when irrigated twice) or those irrigated twice per day in plastic containers (12.4 per plant) (Fig. 2B).

Daily water use. On two (30 Aug. and 21 Oct.) of the three measurement dates, plant DWU was affected by the interaction between N rate and container type (Fig. 1A and C). DWU was affected by the main effect of container type on 25 Sept., with biocontainers (0.177 L per plant) resulting in 67.0% higher DWU compared with plastic container (0.106 L per plant) (Fig. 1B). On 30 Aug., the greatest DWUs resulted from biocontainers using N rates of 10–20 mM (ranging from 0.23 L at 15 mM N to 0.30 L at 10 mM N per plant), greater than all other treatment combinations. DWU in plastic container-grown plants did not vary among N rates from 0 to 20 mM, ranging from 0.08 L at 0 or 10 mM N to 0.15 L per plant at 15 mM N (Fig. 1A). On 21 Oct., plants grown in biocontainers using 20 mM N had the greatest DWU of 0.194 L, greater than all those using N rates from 0 to 15 mM in either container type and comparable to the DWU using 15 mM N and in biocontainers (0.178 L)

(Fig. 1C). Using N rates of 0 to 10 mM, there was no difference in DWU between plants grown in plastic containers or biocontainers. However, when plants were fertilized with higher N rates of 15 and 20 mM, biocontainers resulted in higher DWU than plastic containers.

Plant N concentration and content. N concentration in each structure type (leaf, stem, and root) and average N concentration in the plant were affected by the interaction between N rate and container type, but not by irrigation frequency (Table 2). N content in leaf, stem, and total plant N content were affected similarly. Besides affected by the N rate and container type interaction, root N content was also affected by the main effect of irrigation frequency ($P = 0.0086$). One irrigation per day increased root N content (24.1 mg N) by 17.7% compared with two irrigations (20.5 mg N) per day (Table 3). Generally, N concentrations in leaf, root, and stem showed an increasing trend as N rate increased from 0 to 20 mM (Table 2). Plastic containers and biocontainers resulted in similar N concentrations in stem with N rates of 0 or 5 mM, and in leaves and roots with 0, 5, or 10 mM N. However, plastic containers resulted in higher N concentration than did biocontainers at N rates of 15 and 20 mM in leaf, stem, root, and averaged in the plant. Overall, the highest average plant N concentration (1.01%) resulted from 5 mM N in plastic containers, with the second highest value (0.93%) from 20 mM N in plastic containers.

N content generally increased in leaf, stem, root, and in the entire plant as N rate increased from 0 to 20 mM when plants were grown in biocontainers. When grown in plastic containers, plant N content increased with N rate from 0 to 15 mM and peaked at 15 mM N, with no difference between 15 and 20 mM N or between 10 and 20 mM N treatments. As a result of greater dry weights, biocontainers resulted in greater N content in leaf, stem, root, and the entire plant than plastic containers at N rates of 15 and 20 mM (Table 2).

Discussion

Compared with two irrigations per day, one irrigation per day resulted in higher PGI, root N content, greater root dry weight, root length, root surface area, and greater flower number per plant in plastic containers using N rates of 10 and 20 mM (Fig. 2; Table 3). However, irrigation frequency did not affect dry weight of leaf or stem, SPAD reading, leaf area, or plant N uptake in terms of N concentration and content (except for root N content). By irrigating azalea plants with the same total amount of water, but through two irrigation events instead of one, we assumed there would be reduced leaching of N fertilizer as was shown by Fare et al. (1994) and increasing N uptake. Increasing irrigation frequency was found by Scagel et al. (2011) to decrease water stress of *Rhododendron* cultivars ‘P.J.M. Compact’ (evergreen), ‘English Roseum’ (evergreen), and ‘Gibraltar’ (deciduous). Scagel et al. (2011) attributed

such effect to altered N availability in the substrate or the roots’ ability to take up N. However, irrigation frequency, one or two irrigations per day with the same total amount of water, did not affect N uptake of Encore® azalea ‘Chiffon’ in the present study, an evergreen and slow-growing dwarf cultivar. Rather, one irrigation was more beneficial to root growth in terms of root dry weight, length, surface area, and N content compared with two irrigations per day. Better root growth may have contributed to a larger plant aboveground (higher PGI), or the better root growth may have been sustained by the increased carbohydrate supply from the larger canopy (Chen and Lieth, 1993). Increased irrigation frequency was reported to increase nutrient availability by maintaining a higher conductivity in the substrate (Levin et al., 1980); however, azaleas favor good substrate drainage (Larson, 1993). It is likely that azalea plant benefited from longer period between irrigation events when container moisture may have dropped to a lower level with one irrigation compared with two irrigations per day. Such a theory needs to be confirmed by further studies in which substrate moisture is closely monitored.

When evaluating the feasibility of using biodegradable containers as sustainable alternative to traditional petroleum-based plastic containers, the major focus has been on aspects such as plant quality and water consumption characteristics (Koeser et al., 2013a; Wang et al., 2015), the longevity/physical properties of the biocontainer (Beeks and Evans, 2013; Evans and Karcher, 2004; Koeser et al., 2013b; Li et al., 2015), and production cost (Brumfield et al., 2015). Biocontainers of various types were shown to produce plants of as high quality as plants grown in traditional plastic containers (Evans and Hensley, 2004; Evans and Karcher, 2004; Li et al., 2015). In the present study, the paper biocontainer produced azalea plant of better quality than those grown in plastic containers, with greater dry weights (leaf, stem, root, or total plant) at high N rates of 10–20 mM. Beeks and Evans (2013) reported greater root dry weight of ‘Rainier Purple’ cyclamen (*Cylamen persicum*) when grown in paper and wood fiber containers than in plastic containers, consistent with our results where biocontainer-grown plants had greater root dry weight, root length, and root surface area at higher N rates (15 and 20 mM).

Compared with the larger plant produced using the paper biocontainers, use of plastic containers and one irrigation per day resulted in higher flower number per plant (Fig. 2B). This indicates a competitive relationship between vegetative and reproductive growth of azalea plant. A grower’s choice of container can be made according to their production purpose, whether it is for better-established plant vegetatively or for more flowers.

In our study, use of the paper biocontainer resulted in greater DWU than plastic containers, consistent with results of Wang et al. (2015) in which containers made from

recycled paper used more water than black plastic containers because of the porous nature of the container sidewall (Koeser et al., 2013a). In the present study, the difference in water use between biocontainers and plastic containers resulted from higher N rates (10, 15, and 20 mm N). Under higher N rates of 10–20 mm, plants had higher PGI and dry weights, suggesting that the difference in water use was not merely a function of evaporation through substrate surface and container sidewall, but also affected by different plant growth between container types.

Evapotranspiration, on the other hand, is thought to have a major influence on reducing substrate temperature and help alleviate heat stress during summer in southeastern states such as Mississippi (Nambuthiri et al., 2015). Average maximum daily temperature during summer from June to September ranged from 92 to 96 °F in Starkville, MS (USDA-NRCS, 2018). The evaporative cooling resulting from the increased water loss from container sidewall may have promoted root growth in biocontainers. In addition, the paper biocontainer has a lighter color than black plastic, absorbing less heat and the porous sidewall increases aeration in the substrate, both of which are beneficial for root growth. It is possible better root growth contributed to increased growth of aboveground parts of azalea plant. Therefore, improved vegetative growth in the biocontainer possibly resulted from cooler substrate temperature and better aeration than black plastic containers. Biocontainers also increased plant N uptake at high N rates of 15 and 20 mm. N uptake of a given species is driven by nutrient availability in the growing substrate externally and growth demand under certain growth conditions internally (Gastal and Lemaire, 2002). Given similar nutrient availability externally at a given N rate, biocontainers may have increased N demand of azalea plant by promoting growth in terms of PGI and dry weights than plastic container-grown plants.

As for the economical aspect of using biocontainers as sustainable alternative to plastic containers, the main difference in cost of production between a plastic- and a biocontainer production system was attributed to the price of the pot (Brumfield et al., 2015). Increased water use associated with biocontainers was considered to be an insignificant cost in relation to the entire production process (Brumfield et al., 2015). Although biocontainers tend to be more expensive than their plastic counterparts, the advantage of improved plant growth for certain species (Encore® azalea ‘Chiffon’ in this study) may help promote adoption of biocontainers. On the other hand, growers have a positive attitude toward adopting sustainable practices such as using biodegradable containers (Hall et al., 2009) and consumers are thought to be willing to pay a premium for plant grown in nonplastic containers (Khachatryan et al., 2014); both are promising aspects in promoting the use of biodegradable containers. However, with

long-term nursery production, concerns center on the longevity and other physical properties of biodegradable containers. In our previous study, biocontainers made from the same material, used in a pot-in-pot production system, were recommended to be used for production cycle no longer than 1 year as decomposition of containers may not withstand handling pressure during plant harvest (Li et al., 2015). Degradation of biocontainers was thought to be related to irrigation practices and root growth vigor of certain plant species. In this study, most biocontainers remained intact with no obvious sign of degradation by Nov. 2013 (32 weeks after transplanting). There were a few broken bottoms from some biocontainers at the end of the growing season where the plant had a root system expanding throughout the container under high N rates. The paper biocontainers used in this study should not be used for multiple-year nursery production.

In summary, PGI and dry weight of plastic container-grown plants increased using N rates from 0 to 10 mm and remained similar at 10–20 mm N. By comparison, when grown in biocontainers, both PGI and dry weight increased from 0 to 15 mm N with no difference using 15 and 20 mm N. In our study, the porous container sidewall and light color of biocontainers provided azalea plants with a growth environment leading to higher PGI and dry weight. Improved plant growth in biocontainers contributed to higher N demand and higher N content found in plants grown in biocontainers compared with those grown in plastic containers as a result of better growth using 15 and 20 mm N. One irrigation per day resulted in greater root growth and better flower production, but irrigation frequency did not affect plant N uptake. Optimum fertilization for Encore® azalea ‘Chiffon’ was 10 mm N when grown in plastic containers and 15 mm N in biocontainers.

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