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Container Color and Compost Substrate Affect Root Zone Temperature and Growth of "Green Giant" Arborvitae

Anthony L. Witcher [1,*], Jeremy M. Pickens [2] and Eugene K. Blythe [3]

[1] Department of Agricultural and Environmental Sciences, Otis L. Floyd Nursery Research Center, Tennessee State University, McMinnville, TN 37110, USA
[2] Department of Horticulture, Auburn University, Auburn, AL 36849, USA; jeremy.pickens@auburn.edu
[3] College of Agriculture, Auburn University, Auburn, AL 36849, USA; blythek@auburn.edu
* Correspondence: awitcher@tnstate.edu

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Abstract: Container-grown nursery crops are commonly exposed to root zone stress due to inadequate moisture and supraoptimal root zone temperature (RZT). Compost substrates can improve water and nutrient retention but plant responses can vary due to physical and chemical properties. Dark color containers absorb solar radiation through the container side wall leading to excessive heat buildup in the substrate, yet white containers can reduce RZT. Compost substrates and container color were examined for effects on RZT and growth of "Green Giant" arborvitae (*Thuja standishii* × *plicata* "Green Giant"). "Green Giant" arborvitae were transplanted into white or black containers (11.3 L) filled with a pine bark substrate (PB) or PB mixed with compost (C) at two different proportions [PB:C (9:1) and PB:C (7:3)]. White containers reduced maximum RZT by up to 7 °C and RZT remained above 38 °C for only 3% of the time compared to 21% of the time in black containers. Shoot growth increased over 50% in white containers compared to black containers. Compost increased substrate volumetric water content (VWC), increased shoot growth by up to 24%, and reduced total irrigation volume by up to 40%. Utilizing white containers for minimizing RZT and compost-amended substrates to maintain adequate VWC can improve root and shoot growth and overall crop quality while reducing nursery production inputs.

Keywords: *Thuja standishii* × *plicata*; container production; nursery production; volumetric water content

1. Introduction

Container-grown nursery crops require adequate moisture in the root zone throughout the production cycle for optimum growth. Pine bark (PB) is the most common substrate component used in the eastern United States, but PB typically has high air-filled porosity and low water-holding capacity resulting in low water and nutrient retention properties [1]. Nevertheless, PB has become a relatively universal substrate for producing a wide range of nursery crop species. Pine bark is acquired from different local or regional sources, thus the age and physical structure of PB can vary greatly depending on how long the material has been stored and how it has been processed [2]. These variations will result in substrates and crops with different irrigation demands and may result in over or underwatering if not managed properly, leading to crop stress and nutrient leaching. Pine bark with air-filled porosity above the recommended maximum (30%) should be modified to increase container capacity between 45% and 65%, thus improving irrigation efficiency [3,4].

Sphagnum peatmoss is commonly added to PB for increased water retention, yet composted materials are a viable alternative to peatmoss. The benefits of compost include greater water retention, enhanced nutrient availability, and potential disease suppressive properties due to increased microbial activity [5,6]. Composts can be produced from a variety of feedstocks including municipal green wastes, animal manure, and biosolids [7,8]. As a result, composts are more widely produced, regionally available, and less expensive compared to peatmoss [9,10]. Compost-amended substrates have been evaluated for production of a number of horticultural crops, but plant response can be positive or negative based on the type and amount of compost used [10]. Composts typically have a high proportion of fine particles that contribute to greater water retention, yet high compost content can lead to reduced plant growth due to low aeration and poor drainage. Substrate chemical properties can also be altered with the addition of compost. Compost produced from horse manure can vary due to the amount of bedding included in the feedstock, with pH ranging from 6.2 to 8.1 and high levels of soluble salts [11]. Vermicompost is produced through the decomposition of organic matter utilizing earthworms and microorganisms and a variety of organic wastes can be used including animal manure and crop residues which can affect the chemical and physical properties [12]. As a result, compost materials should not compose more than 50% of a container substrate [13].

Container-grown crops are frequently exposed to supraoptimal root zone temperature (RZT) in excess of 54 °C during the growing season [14]. Root growth can cease at RZT above 38 °C and permanent root damage can occur with short-term (30-min) exposure of RZT above 46 °C [14]. Exposure to critical RZT (above 38 °C) for extended periods of time causes long-term plant damage exhibited as reduced growth and quality and even mortality in sensitive species [14,15]. Container color and substrate porosity can affect RZT by altering the rate of heat buildup or dissipation. Dark-colored containers exacerbate the effects of supraoptimal RZT due to increased solar radiation absorption through the container side wall leading to excessive heat buildup in the substrate [16]. Markham et al. [15] reported RZT was reduced by 7.7 °C in white containers compared to conventional black containers, suggesting light color containers may provide benefits for certain plant species. Substrates with lower air-filled porosity may minimize fluctuations in RZT by utilizing the thermal conductivity properties of water, yet excessive substrate moisture content must be avoided [14].

Plant species such as "Green Giant" arborvitae (*Thuja standishii* × *plicata* 'Green Giant') may be considered heat tolerant and adaptable to various soil types yet can be sensitive to high RZT and reduced moisture level. For example, "Green Giant" arborvitae grew larger and produced more root biomass in white containers compared to black containers due to extended exposure to RZT over 38 °C [17]. In the same study, peatmoss-amended substrate resulted in larger plants due to increased volumetric water content (VWC) compared to pine bark alone. Compost may be a suitable substitute for peatmoss, yet little information is available regarding VWC and RZT in various types or proportions of compost.

Identifying practical and cost effective methods for reducing RZT in container-grown crops would lead to improved productivity and crop quality. Black containers are still predominantly used throughout the nursery industry and only a small number of producers utilize compost substrates. Demonstrating the factors (container or substrate) that maximize crop growth may improve commercial adoption of these practices. Therefore, the objective of this research was to evaluate the combined effects of container color and compost substrate on growth of "Green Giant" arborvitae.

2. Materials and Methods

Two separate studies were conducted concurrently at the Tennessee State University Otis L. Floyd Nursery Research Center in McMinnville, TN (USDA Plant Hardiness Zone 7a) and the Auburn University Ornamental Horticulture Research Center in Mobile, AL (USDA Plant Hardiness Zone 8b). The studies were conducted at two locations due to potential differences in environmental conditions which may affect plant growth, including temperature and rainfall. The average daily temperature in Tennessee (TN) ranged from 23.5 °C (May) to 26.1 °C (July) and ranged from 18.1 °C (May) to 27.1 °C (July) in Alabama (AL). Average daily high temperature was greatest in July (34.3 °C) and June (32.9 °C) in TN and AL, respectively. Rainfall totaled 84.8 cm (TN) and 115.8 cm (AL) over the duration of each study.

Black and white nursery containers (11.3 L; PF1200; Nursery Supplies Inc., Kissimmee, FL, USA) were evaluated in combination with three container substrates for a total of six treatments. Substrates included pine bark alone (PB) or combined (v:v) with compost (C) at two different proportions [PB:C (9:1) and PB:C (7:3)]. Pine bark was obtained from Morton's Horticultural Products (McMinnville, TN) and from Longleaf Mulch (Semmes, AL) for the Tennessee (TN) and Alabama (AL) studies, respectively. Compost was obtained from Silver Bait LLC (vermicompost; Coalmont, TN) and Faulkner Farms (windrowed composted horse manure; Silverhill, AL) for the TN and AL studies, respectively. All substrates were amended (per 1 m^3) with 7.7 kg 18N-2.6P-6.6K controlled-release fertilizer (18-6-8 Nutricote® Total Type 270; Florikan, Sarasota, FL, USA), 3.6 kg dolomitic limestone, and 0.9 kg micronutrient granules (Micromax; ICL Specialty Fertilizers, Summerville, SC). "Green Giant" arborvitae (7.6 cm diameter containers) were transplanted on 3 April 2018 (AL) or 3 May 2018 (TN) into each treatment with 12 replicates per treatment and plants were arranged on a gravel container pad in a randomized complete block design. To provide maximum container surface area to sunlight, plants were spaced 0.9 m apart.

Separate irrigation controller zones were used for each treatment to monitor and adjust irrigation application rates. Plants were irrigated three times daily (11am, 12pm, and 1pm) using a modified dribble ring (15.2 cm diameter; Dramm Corp., Manitowoc, WI, USA) fitted with a pressure-compensating emitter (8 L h^{-1}; Netafim USA, Fresno, CA). Irrigation application volume for each treatment was adjusted biweekly based on replacement of daily water use/loss from the previous 24 h period. Decagon 5TE (AL) and 5TM (TN) sensors and EM50 data loggers (Decagon Devices Inc., Pullman, WA) were used to measure and record RZT and volumetric water content (VWC; $m^3 \cdot m^{-3}$) every 15 min throughout both studies. Sensors were positioned vertically approximately 4.3 cm from the container sidewall and placed midway between the substrate surface and bottom of the container. Plant height and diameter were measured at 30, 60, 150, and 180 days after planting (DAP) in AL and 30, 60, 90, 120, and 150 DAP in TN. Growth index was calculated [(height + width at widest point + perpendicular width)/3] and increase in plant height and growth index was also reported (increase = final − initial). The studies were terminated at 180 (AL) and 150 (TN) DAP and plants were destructively harvested. Shoot dry weight (n = 12) and root dry weight (n = 12) were measured after samples were oven dried at 70 °C for approximately 7 days. Substrate pH and electrical conductivity (EC) were recorded using the pour-through method [18] at 60, 120, and 180 DAP (AL) and at 30, 90, and 150 DAP (TN). The percentage of time roots were exposed to temperatures above critical thresholds (38 °C and 46 °C) mentioned by Ingram et al. [14] and this was calculated using the total number of data recordings during daylight hours. Substrate physical properties (n = 3) including air space, container capacity, total porosity, and bulk density were determined using porometer analysis [19].

Multifactor data were analyzed with linear mixed models using the GLIMMIX procedure of SAS (Version 9.3; SAS Institute, Inc., Cary, NC, USA) by first testing for an interaction between treatment factors (container type and substrate). When there was an interaction between treatment factors, levels of substrate were compared within each container. Porometer data were analyzed with linear models using the GLIMMIX procedure of SAS. P-values for all simultaneous comparisons were adjusted using the Tukey method to maintain an overall significance level of α = 0.05.

3. Results

3.1. Substrate Physical and Chemical Properties

The PB used in each study was from different sources which affected substrate physical properties. Substrate air space and container capacity was 8% and 9% greater, respectively, in TN compared with AL. Substrate air space was greater in PB compared to PB:C (7:3) for both the AL and TN studies (Table 1). Air space was 11% (TN) and 3% (AL) less in substrates amended with 30% compost compared to PB. Container capacity was 7% and 2% greater in PB:C (7:3) compared to PB in the TN and AL studies, respectively. In the TN study, the addition of 10% compost had no significant effect on air space but did increase container capacity. Total porosity was greatest in PB:C (9:1) for the TN study, but PB:C (9:1) had similar total porosity compared with the other substrates in the AL study. Compost had the lowest air space and greatest container capacity compared with the other substrates in both studies.

Table 1. Physical properties (n = 3) of substrate components and substrates for production of "Green Giant" arborvitae in Tennessee (McMinnville) and Alabama (Mobile).

Substrate [z]	Air Space [y]	Container Capacity	Total Porosity	Bulk Density
		(% volume)		($g \cdot cm^{-3}$)
		Tennessee		
PB	31.6 a [x]	48.8 c	80.4 b	0.232 b
PB:C (9:1)	30.0 a	54.5 b	84.5 a	0.229 b
PB:C (7:3)	20.0 b	55.5 b	75.5 c	0.288 a
C	7.7 c	76.9 a	84.6 a	0.289 a
		Alabama		
PB	23.8 b	39.8 c	63.6 a	0.260 d
PB:C (9:1)	24.7 a	38.6 d	63.3 ab	0.291 c
PB:C (7:3)	20.8 c	41.8 b	62.6 b	0.368 b
C	9.9 d	53.2 a	63.1 ab	0.590 a

[z] Substrate: Pine bark alone (PB), compost alone (C), or combined (v:v) at two rates [PB:C (9:1) and PB:C (7:3)]. [y] Data obtained using the North Carolina State University porometer method [19]. [x] Means followed by the same letter within a location are not significantly different (α = 0.05).

Substrate pH ranged from 6.3 to 7.6 (TN) and from 3.7 to 6.4 (AL) for all treatments throughout both studies (Table 2). In the TN study, substrate pH remained above the recommended range of 4.5 to 6.5 [20] except at 90 DAP for PB:C (7:3) and PB:C (9:1) yet remained within the recommended range throughout the AL study except for PB and PB:C (9:1) at 180 DAP. The pH of the composts alone prior to mixing was 7.3 (TN) and 6.9 (AL). The effects of compost amendment on substrate pH differed between the studies, decreasing pH in the TN study while increasing pH in the AL study. Compost substrates had greater substrate EC compared to PB in the TN study except at project termination where no differences were observed. At 30 and 90 DAP, substrate EC was over two times greater in compost substrates compared to PB. Container color also had an effect on substrate EC, with lower EC in white containers compared to black containers at 90 and 150 DAP. In the AL study, compost had no significant effect on substrate EC. Compost EC was also analyzed prior to mixing and was over four times greater for AL (2622 $mS \cdot cm^{-1}$) compared to TN (612 $mS \cdot cm^{-1}$).

3.2. Plant Growth

In the TN study, there was an interaction between container color and substrate for plant height at 60 and 120 DAP (Table 3). Plant height was lowest for PB:C (7:3) in white containers but similar between PB and each compost substrate in the black container. Height increase was greatest in the white container but similar among all substrates. Plants in PB:C (9:1) had the greatest growth index, growth index increase, and shoot dry weight, yet root dry weight was similar among all substrates in the black container and similar for PB and PB:C (9:1) in the white container (Table 4).

In the AL study, final plant height and plant height increase was greatest in the white container, substrate had no significant effect on plant height, and height increase was similar between the compost substrates (Table 3). Plants in white containers also had the greatest growth index increase, shoot dry weight, and root dry weight (Table 4). Although shoot dry weight was greatest for PB:C (7:3), substrate did not affect growth index, growth index increase, or root dry weight.

Table 2. Substrate pH and electrical conductivity ($n = 4$) of "Green Giant" arborvitae grown in different types of containers and substrates in Tennessee (McMinnville) and Alabama (Mobile).

		30 DAP [x]		**90 DAP**		**150 DAP**		**60 DAP**		**120 DAP**		**180 DAP**	
		pH	**EC** [w]	**pH**	**EC**	**pH**	**EC**	**pH**	**EC**	**pH**	**EC**	**pH**	**EC**
		Tennessee						**Alabama**					
		Significance of treatment factors											
Container [z]		0.0002	<0.0001	0.0003	0.0014	<0.0001	0.0004	0.7262	0.9204	0.0113	0.0002	0.0854	0.7841
Substrate [y]		<0.0001	<0.0001	0.0011	0.0003	<0.0001	0.1817	0.4976	0.0759	0.0003	0.8723	<0.0001	0.1655
Cont * Sub		0.4336	0.052	0.3343	0.3417	0.1572	0.8039	0.4975	0.3613	0.028	0.6604	0.6882	0.5352
		Least squares means for main effects											
Container	Substrate												
Black		7.3 b [v]	-	6.5 b	3366 a	6.8 b	965 a	6.2 a	1902 a	-	826 a	4.4 a	1127 a
White		7.5 a	-	7.0 a	2001 b	7.3 a	479 b	6.2 a	1884 a	-	437 b	4.7 a	1098 a
	PB	7.6 A	-	7.1 A	1410 B	7.3 A	611 A	6.3 A	1609 A	-	661 A	3.7 C	1237 A
	PB:C (9:1)	7.3 B	-	6.7 B	2986 A	7.0 B	694 A	6.2 A	1923 A	-	625 A	4.3 B	1121 A
	PB:C (7:3)	7.2 B	-	6.5 B	3654 A	6.8 C	860 A	6.1 A	2147 A	-	609 A	5.6 A	978 A
		Treatment least squares means grouped by substrate											
Container	Substrate												
Black	PB	7.5	705 c	6.9	1721	7.1	804	6.4	1463	4.9 b	799	3.7	1335
	PB:C (9:1)	7.2	1700 b	6.3	3893	6.7	967	6.2	1920	4.7 b	848	4.1	1073
	PB:C (7:3)	7.1	2220 a	6.3	4483	6.6	1123	6.1	2323	5.8 a	831	5.3	973
White	PB	7.6	518 B	7.2	1099	7.5	417	6.2	1754	5.0 B	523	3.8	1139
	PB:C (9:1)	7.5	1070 A	7.0	2079	7.3	422	6.2	1926	5.8 A	401	4.5	1170
	PB:C (7:3)	7.4	1411 A	6.7	2825	7.0	597	6.1	1971	6.0 A	388	5.9	984

[z] Container with black or white exterior (11.3 L; PF1200; Nursery Supplies Inc., Kissimmee, FL). [y] Substrate: Pine bark alone (PB) or combined (v:v) with compost (C) at two rates [PB:C (9:1) and PB:C (7:3)]. [x] DAP = days after planting. [w] EC = electrical conductivity; $mS \cdot cm^{-1} = 1$ mmho/cm. [v] When the interaction term (Cont * Sub) in the model is not significant ($p > 0.10$), main effects means for levels within each treatment factor followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$). When the interaction term in the model is significant ($p \leq 0.10$), simple effects means (treatment means for container grouped within substrate) followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$); otherwise, the treatment means are presented without letter groupings for informational purposes.

Table 3. Plant height and height increase of "Green Giant" arborvitae grown in two containers and three substrates in Tennessee (McMinnville) and Alabama (Mobile).

		Plant Height (cm)			**Plant Height (cm)**		
		60 DAP [x]	**150 DAP**	**Increase** [w]	**60 DAP**	**180 DAP**	**Increase**
			Tennessee			**Alabama**	
				Significance of treatment factors			
Container [z]		0.0313	<0.0001	<0.0001	0.1400	<0.0001	<0.0001
Substrate [y]		<0.0001	0.0003	0.8208	0.7755	0.2047	0.0510
Cont * Sub		0.0844	0.0073	0.1675	0.0766	0.1794	0.3254
				Least squares means for main effects			
Container	Substrate						
Black		-	-	20.8 b	-	60.9 b	24.0 b
White		-	-	36.7 a	-	71.4 a	34.5 a
	PB	-	-	29.0 A	-	64.9 A	27.2 B
	PB:C (9:1)	-	-	29.1 A	-	65.6 A	29.4 AB
	PB:C (7:3)	-	-	28.1 A	-	68.0 A	31.1 A
				Treatment least squares means grouped by substrate			
Container	Substrate						
	PB	49.7 ab [v]	63.3 a	19.9	42.1 a	58.5	21.5
Black	PB:C (9:1)	51.2 a	64.2 a	20.4	43.3 a	62.3	25.4
	PB:C (7:3)	46.6 b	61.7 a	22.1	43.6 a	61.9	25.0
	PB	54.2 A	84.4 A	38.2	45.0 A	71.3	33.0
White	PB:C (9:1)	54.5 A	80.8 A	37.7	43.0 A	69	33.3
	PB:C (7:3)	45.6 B	70.6 B	34.1	43.7 A	74	37.2

[z] Container with black or white exterior (11.3 L; PF1200; Nursery Supplies Inc., Kissimmee, FL). [y] Substrate: Pine bark alone (PB) or combined (v:v) with compost (C) at two rates [PB:C (9:1) and PB:C (7:3)]. [x] DAP = days after planting. [w] Increase = final plant height—initial plant height. [v] When the interaction term (Cont * Sub) in the model is not significant ($p > 0.10$), main effects means for levels within each treatment factor followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$). When the interaction term in the model is significant ($p \leq 0.10$), simple effects means (treatment means for container grouped within substrate) followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$); otherwise, the treatment means are presented without letter groupings for informational purposes.

3.3. Root Zone Temperature and Volumetric Water Content

Root zone temperature remained above the 38 °C threshold for longer periods of time in black containers compared to white containers, regardless of substrate. There was an interaction between container color and substrate for percentage of time at or above 38 °C in the TN study (Table 5). Substrate had no significant effect on percentage of time above 38 °C in black containers (ranging 16.8 to 18.1%), whereas RZT remained above 38 °C for only 1.1% of the time in PB:C (7:3) in white containers. In the AL study, RZT was above 38 °C for 18% longer in black containers but substrate did not significantly affect time above 38 °C. Although RZT only remained above 46 °C 0.7% (TN) and 0.1 % (AL) of the time in black containers, RZT in white containers did not reach this threshold in either study.

Volumetric water content tended to increase with the addition of compost and with compost proportion in both studies, yet differences in VWC varied among the substrates. In the TN study, VWC was greatest in PB:C (7:3) and lowest in PB for July and August (Table 6). Volumetric water content was lowest in PB for the black container in June, September, and October, yet there were no differences in VWC among the substrates in the white container for September and October. Throughout the study, VWC remained above 33% in all treatments. In the AL study, VWC was lowest in PB and greatest in PB:C (7:3) throughout the study (data not shown) and VWC ranged between 21% and 29% throughout the study for all treatments.

Table 4. Plant growth index ($n = 12$), growth index increase, and dry weight (shoot and root) ($n = 6$) of "Green Giant" arborvitae grown in different types of containers and substrates in Tennessee (McMinnville) and Alabama (Mobile).

		Growth Index [x]			**Shoot Dry Wt (g)**	**Root Dry Wt (g)**	**Growth Index**			**Shoot Dry Wt (g)**	**Root Dry Wt (g)**
		60 DAP [w]	**150 DAP**	**Increase** [v]			**60 DAP**	**180 DAP**	**Increase**		
		Tennessee					**Alabama**				
Significance of treatment factors											
Container [z]		0.0071	<0.0001	<0.0001	<0.0001	<0.0001	0.0620	<0.0001	<0.0001	<0.0001	<0.0001
Substrate [y]		<0.0001	0.0098	0.0629	<0.0001	0.0337	0.4090	0.0554	0.0583	0.0034	0.0955
Cont * Sub		0.5754	0.1603	0.6297	0.2373	0.0381	0.2306	0.0973	0.3169	0.2711	0.2765
Least squares means for main effects											
Container	Substrate										
Black		34.1 b [u]	47.6 b	20.2 b	85.3 b	-	29.1 a	-	21.8 b	60.2 b	3.1 b
White		35.6 a	58.3 a	31.3 a	133.3 a	-	30.0 a	-	29.6 a	92.3 a	8.4 a
	PB	35.2 B	52.5 B	24.5 B	100.8 B	-	29.5 A	-	24.7 A	71.7 B	5.6 A
	PB:C (9:1)	36.7 A	55.0 A	26.9 A	124.3 A	-	29.2 A	-	25.0 A	73.0 B	5.4 A
	PB:C (7:3)	32.7 C	51.5 B	25.9 AB	102.7 B	-	30.0 A	-	27.5 A	84.1 A	6.4 A
Treatment least squares means grouped by substrate											
Container	Substrate										
	PB	34.3	45.9	18.4	72.3	8.6 a	28.6	42.8 a	19.9	56.5	2.9
Black	PB:C (9:1)	35.7	49.9	21.8	100.1	10.0 a	29.3	45.1 a	22.1	59.6	3.2
	PB:C (7:3)	32.4	47.1	20.5	83.6	9.4 a	29.4	45.8 a	23.5	64.6	3.4
	PB	36.1	59.0	30.6	129.4	16.9 A	30.4	53.1 AB	29.5	86.9	8.3
White	PB:C (9:1)	37.6	60.1	32.1	148.6	17.5 A	29.1	50.7 B	27.9	86.4	7.6
	PB:C (7:3)	33.0	55.9	31.2	121.9	13.6 B	30.5	54.7 A	31.4	103.7	9.3

[z] Container with black or white exterior (11.3 L; PF1200; Nursery Supplies Inc., Kissimmee, FL); [y] Substrate: Pine bark alone (PB) or combined (v:v) with compost at two rates [PB:C (9:1) and PB:C (7:3)]. [x] Growth index = (height + width at widest point + perpendicular width)/3; [w] DAP = days after planting; [v] Increase = final growth index—initial growth index; [u] When the interaction term (Cont * Sub) in the model is not significant ($p > 0.10$), main effects means for levels within each treatment factor followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$). When the interaction term in the model is significant ($p \leq 0.10$), simple effects means (treatment means for container grouped within substrate) followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$); otherwise, the treatment means are presented without letter groupings for informational purposes.

Table 5. Percent of time (n = 3) root zone temperature (RZT) remained above critical thresholds (38 °C and 46 °C) and maximum RZT during daylight hours for "Green Giant" arborvitae grown in different types of containers and substrates in Tennessee (McMinnville) and Alabama (Mobile).

		38 °C (%)	46 °C (%)	Maximum (°C)	38 °C (%)	46 °C (%)	Maximum (°C)
			Tennessee			**Alabama**	
		Significance of treatment factors					
Container [z]		<0.0001	<0.0001	-	<0.0001	0.0462	-
Substrate [y]		0.0041	0.7934	-	0.1811	0.0373	-
Cont * Sub		0.0024	0.9414	-	0.2475	0.1997	-
		Least squares means for main effects					
Container	Substrate						
Black		-	0.69 a	48.0	21.7 a	0.10 a	45.7
White		-	0.00 b	41.7	3.2 b	0.00 b	40.7
	PB	-	0.22 A	45.0	16.3 A	0.15 A	44.2
	PB:C (9:1)	-	0.30 A	45.4	12.3 A	0.00 B	42.9
	PB:C (7:3)	-	0.45 A	44.1	11.0 A	0.02 AB	42.5
		Treatment least squares means grouped by substrate					
Container	Substrate						
	PB	16.8 a [x]	0.54	-	23.9	0.26	-
Black	PB:C (9:1)	17.4 a	0.75	-	21.0	0.00	-
	PB:C (7:3)	18.1 a	0.76	-	20.2	0.03	-
	PB	4.6 A	0.00	-	4.9	0.00	-
White	PB:C (9:1)	4.0 A	0.00	-	3.6	0.00	-
	PB:C (7:3)	1.1 B	0.00	-	1.8	0.00	-

[z] Container with black or white exterior (11.3 L; PF1200; Nursery Supplies Inc., Kissimmee, FL). [y] Substrate: Pine bark alone (PB) or combined (v:v) with compost at two rates [PB:C (9:1) and PB:C (7:3)]. [x] When the interaction term (Cont * Sub) in the model is not significant ($p > 0.10$), main effects means for levels within each treatment factor followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$). When the interaction term in the model is significant ($p \leq 0.10$), simple effects means (treatment means for container grouped within substrate) followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$); otherwise, the treatment means are presented without letter groupings for informational purposes.

Table 6. Average daytime volumetric water content (n = 3) over a four month period for "Green Giant" arborvitae grown in different types of containers and substrates in Tennessee.

		Volumetric Water Content ($m^3 \cdot m^{-3}$)				
		June	**July**	**Aug.**	**Sept.**	**Oct.**
		Significance of treatment factors				
Container [z]		0.5352	0.3931	0.8672	0.7175	0.6421
Substrate [y]		0.0004	0.0003	0.0005	0.0014	0.0062
Cont * Sub		0.0794	0.1689	0.2079	0.0727	0.0221
		Least squares means for main effects				
Container	Substrate					
Black		-	0.442 a	0.435 a	-	-
White		-	0.399 a	0.410 a	-	-
	PB	-	0.340 C	0.355 C	-	-
	PB:C (9:1)	-	0.418 B	0.417 B	-	-
	PB:C (7:3)	-	0.500 A	0.493 A	-	-
		Treatment least squares means grouped by substrate				
Container	Substrate					
	PB	0.364 b [x]	0.332	0.333	0.362 b	0.360 b
Black	PB:C (9:1)	0.486 a	0.467	0.453	0.491 a	0.472 a
	PB:C (7:3)	0.515 a	0.498	0.492	0.522 a	0.531 a

Table 6. *Cont.*

		Volumetric Water Content ($m^3 \cdot m^{-3}$)				
		June	**July**	**Aug.**	**Sept.**	**Oct.**
White	PB	0.398 B	0.345	0.37	0.419 A	0.440 A
	PB:C (9:1)	0.424 B	0.385	0.394	0.450 A	0.442 A
	PB:C (7:3)	0.514 A	0.502	0.494	0.485 A	0.453 A

[z] Container with black or white exterior (11.3 L; PF1200; Nursery Supplies Inc., Kissimmee, FL). [y] Substrate: Pine bark alone (PB) or combined (v:v) with compost at two rates [PB:C (9:1) and PB:C (7:3)]. [x] When the interaction term (Cont * Sub) in the model is not significant ($p > 0.10$), main effects means for levels within each treatment factor followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$). When the interaction term in the model is significant ($p \leq 0.10$), simple effects means (treatment means for container grouped within substrate) followed by the same lower-case or upper-case letter are not significantly different using the Tukey method for multiple comparisons ($\alpha = 0.05$); otherwise, the treatment means are presented without letter groupings for informational purposes.

4. Discussion

Use of white containers had an overall greater impact on arborvitae plant growth considering the comparatively small differences in growth observed when compost was added to the substrate. Compared to black containers, white containers resulted in 53% (AL) to 56% (TN) greater shoot dry weight while a 17% (AL) to 24% (TN) increase in shoot dry weight occurred between PB and the compost substrates. Similarly, root dry weight increased 72% (TN) to 270% (AL) in white containers yet 8% (TN) to 19% (AL) greater root mass resulted due to the addition of compost to PB. Nevertheless, white containers and compost substrates each provide characteristics beneficial to crop growth and for optimizing production practices.

White containers reduced RZT throughout both studies by minimizing the amount of solar radiation absorbed through the container sidewall. Maximum RZT was 41 °C in the white container (both studies) and reached 48 °C (TN) and 46 °C (AL) in the black container (Table 5). Although RZT was observed above the 38 °C threshold in white containers, RZT remained above 38 °C for only 3% of the time which was 14% (TN) to 18% (AL) lower compared to the black container. The benefits of producing plants in white containers, particularly reduced RZT and improved plant growth, have been well documented [14,15]. In the present study, the extended exposure to supraoptimal RZT in black containers was the main factor attributed to reduced plant performance since all plants received frequent irrigation (three times daily; volume based on plant use) and adequate fertility was maintained (based on substrate EC). "Green Giant" arborvitae is considered a heat tolerant plant and readily adaptable to various soil types [21]. Nevertheless, results of the present study support previous work by Witcher et al. [17] where "Green Giant" arborvitae grown in white containers grew larger and produced more biomass compared with black containers.

The addition of compost resulted in increased plant growth in both the AL and TN studies, but plant response differed by proportion of compost and by study location. Compost increased container capacity compared to PB alone, whereas air space only decreased for PB:C (7:3). Air space was within the recommended range (10% to 30%) for all substrates except for PB (TN), while container capacity was below the recommended range (45% to 65%) [20] for all substrates in the AL study. Compost had a greater impact on air space and container capacity in the TN study due to inherent differences in physical properties between the PB and compost used in each study. In the TN study, air space was 24% greater and container capacity was 28% lower for PB compared to vermicompost. In the AL study, the differences between PB and horse manure compost were much smaller for air space (14%) and container capacity (13%). Nevertheless, VWC increased with compost proportion in both studies corresponding to the increased container capacity. Due to the increased water holding capacity of the compost substrates, total irrigation volume applied was reduced by 27% and 40% (data not shown) for PB:C (9:1) and PB:C (7:3), respectively, compared to PB.

Although VWC was greatest in PB:C (7:3), this did not correspond to maximum plant growth in the TN study. Moore [10] reported plant species can respond differently to the proportion of compost in a substrate and various factors can affect plant growth such as EC, pH, physical properties, and compost maturity [5,6]. Substrate pH decreased with the addition of compost in the TN study yet increased with compost in the AL study due to the higher initial pH of PB in the TN study. All substrates received the same rate of dolomitic lime and controlled release fertilizer, thus differences in pH among substrates were due to the inherent pH of the substrate components. Although the horse manure compost (AL) had a high initial EC (2622 mS·cm^{-1}), substrate EC remained within the desirable range (0.5 to 2 mS·cm^{-1}) throughout both studies except at 90 DAP (TN). As a result, growth in PB:C (7:3) (TN) was likely limited due to reduced air space combined with high VWC which may have led to inadequate root aeration.

The compost used at each site was obtained from different sources and produced from different feedstock which can affect chemical and physical properties [6,22]. For example, composts produced from sewage sludge waste tend to have low air space while composts from coarse cow manure have greater air space [6]. Bachman and Metzger [23] reported vermicompost had varied physical and chemical properties based on the type of parent material used. The physical properties of PB can also vary due to source, processing method, and age [2]. Substrate components typically have a range of particle sizes and when combined with another component the resulting substrate will have different physical properties due to nesting of smaller particles within the larger particles [2,23]. When considering compost-amended substrates, nursery producers should conduct small-scale evaluations to determine optimum compost proportions and amendment rates (fertilizer, lime, etc.) for each combination and to evaluate substrate chemical properties (pH and EC) and plant growth. Each substrate should be placed in a separate irrigation zone and irrigation volume should be adjusted based on plant needs to ensure optimum moisture levels are maintained. All of these factors should be considered when utilizing new substrates.

5. Conclusions

In the present study, arborvitae plants grown in white containers were larger (height and growth index) than plants in black containers that had been grown for 30 additional days. In addition, compost substrates retained more water and fertilizer over time resulting in improved plant growth. White containers significantly reduce RZT and are widely available from various commercial manufacturers in several sizes (2.4 to 19 L). Adopting methods for reducing root zone stress by minimizing RZT and maintaining adequate VWC can improve root and shoot growth and overall crop quality while reducing nursery production inputs.

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