Use of Processed Biofuel Crops for Nursery Substrates[1]

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Abstract

Loblolly pine (*Pinus taeda*) bark availability has decreased, causing shortages in inventory and increased prices for pine bark substrates. One potential alternative to pine bark is the use of biofuel or biomass crops that can be grown locally, harvested, and processed into a suitable substrate. The objective of this research was to assess the suitability of several biofuel crops as alternatives to pine bark in nursery substrates using annual vinca (*Catharanthus roseus*) as a model crop. Across two experiments, switchgrass (*Panicum virgatum*), willow (*Salix* spp.), corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus ×giganteus*) were processed through a hammermill equipped with a 0.95 cm (0.375 in) screen. Pine bark was used as a control. Substrate materials were used either alone, amended with 20% (v/v) sphagnum peat moss, or amended with 20% (v/v) sphagnum peat moss and 10% (v/v) municipal solid waste compost. Biofuel-based substrates tended to have greater air space and less container capacity than pine bark substrate. Amending with peat moss, or peat moss and municipal solid waste compost reduced air space and increased container capacity of all substrates. Substrate pH of biofuel-based substrates was higher than pine bark substrates, and was neutral to slightly alkaline. Amending with peat moss reduced pH of biofuel substrates to levels considered more ideal for annual vinca growth. Foliar calcium, magnesium, and iron levels were low across all treatments, although visual foliar deficiency symptoms were not apparent. Shoot growth was greatest in switchgrass and pine bark substrates. Plant growth differed among biofuel and pine bark substrates; however, all plants were considered marketable at the conclusion of the experiment. Modification of chemical and physical properties for each substrate type will be necessary.

Index words: alternative substrate, giant miscanthus, switchgrass, willow, corn stover.

Significance to the Nursery Industry

Decreasing availability and increasing price for pine bark is a growing concern among nursery producers east of the Rocky Mountains. Alternatives to pine bark are needed. While agricultural and manufacturing industries once generated large volumes of waste or residual materials (for example, pine bark), ever-growing interest in bio-energy has greatly reduced availability of those materials. The abundance of farmland in most of the nursery-producing regions of the United States led us to consider the concept of harvesting biofuel crops and processing them into a substrate. The objective of this research was to determine if several commonly grown biofuel crops could be processed and amended to produce a substrate suitable for production of containerized ornamental plants. Switchgrass (*Panicum virgatum*), willow (*Salix* spp.), corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus ×giganteus*) were processed through a hammermill equipped with a 0.95 cm (0.375 in) screen. Pine bark was used as a control. All materials were used either alone, amended with 20% (v/v) sphagnum peat moss, or amended with 20% (v/v) sphagnum peat moss and 10% (v/v) municipal solid waste compost. Plant growth was acceptable in all biofuel-based substrates; however, chemical and physical properties for each substrate will require some modification.

Introduction

Pine bark, the principal component of container nursery substrates east of the Rocky Mountains, is primarily generated in lumber and paper mills located throughout the southern United States. A decline in demand for forest products has reduced the volume of available pine bark for horticultural uses (personal observation). Nurseries in upper Midwest states import pine bark from mills located primarily in southern states via truck or rail cars. Increased fuel costs for transporting pine bark over great distances has further increased prices in Midwest states.

Recent research has shown that substrates derived from entire pine trees (as opposed to just pine bark) are suitable for production of nursery and greenhouse crops (2, 6, 14). However, traditional wood biomasses are not abundant in upper Midwest states as forestry activities are much less common compared to western and southern states (11). Farmland, however, is abundant and thus any material that can be generated on local farmlands could potentially be used as an alternative substrate. Crops generically classified as biofuels are of particular interest because they inherently generate large volumes of biomass. Switchgrass (*Panicum virgatum*), willow (*Salix* spp.), corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus ×giganteus*) are currently grown throughout upper Midwest states. The objective of this research was to use annual vinca (*Catharanthus roseus* 'Pacifica Blush') to assess the potential for each material as the primary component in container nursery substrates.

Materials and Methods

Switchgrass bales were obtained from a farm in Meadeville, PA. Switchgrass was cut and baled in early spring 2008 and 2009 for Expts. 1 and 2, respectively. Miscanthus, obtained from the University of Illinois Energy Biosciences Institute (Urbana, IL), was baled in early Spring 2009. Willow chips were obtained from a willow biofuel farm in Fredonia, NY. Willows were cut in late winter, processed through a chipper, and stored in a Gaylord box (corrugated pallet box, approximately 0.76 m^3 (1 yd^3) vol). Corn stover was harvested from a farm in Wooster, OH in late fall and

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baled. All baled and boxed materials were stored in a barn until needed. One day prior to starting each experiment, materials were processed through a 15 HP hammermill (C.S. Bell, Tiffin, OH) equipped with a 0.95 cm (0.375 in) screen. Pine bark was obtained from Fafard (Conrad Fafard Inc., Agawam, MA). Particle size distribution of substrate materials was determined using approximately 100 cm^3 (0.1 qt) oven dried substrate [72C (162F)] passed through the following sieves: 19.0, 12.5, 6.30, 4.0, 2.8, 2.0,1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm (0.75, 0.5, and 0.25 in, and nos. 5, 7, 10, 14, 18, 25, 35, 45, 60, 80, and 140). Particles ≤ 0.11 mm (no. 140 screen) were collected in a pan. Sieves and pan were shaken for 3 min with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations·min^{-1}, 150 taps·min^{-1}) (W.S. Tyler, Mentor, OH).

Experiment 1. The experiment was conducted in a polyethylene-covered hoophouse in Wooster, OH. Treatment design was a four by two factorial, with four substrates and two peat moss amendment rates. The four substrates included switchgrass, willow chip, corn stover, and pine bark. Substrates were amended with either 0 or 20% sphagnum peat moss, by volume. All substrates were amended with 0.9 kg·m^{-3} (1.5 lb·yd^{-3}) Micromax (The Scotts Co., Marysville, OH) micronutrients and 1.2 kg·m^{-3} (2 lb·yd^{-3}) gypsum. Substrates were put in containers 15 cm (6 in) tall and wide, and potted with a single vinca (*Catharanthus roseus* 'Pacifica Blush') from a 50-cell plug on February 4, 2009. Vinca were 3 to 5 cm (1.2 to 2.0 in) tall and not yet branched or flowering at the time of potting. All containers were topdressed with 20 g (0.7 oz) Osmocote 18-6-12 (The Scotts Co.) controlled release fertilizer. Containers were overhead irrigated via an irrigation system as needed. Light was supplemented with sodium vapor lights from 6 am to 8 pm. Thermostat heat and cool points were set at 18 and 24C (64 and 75F), respectively.

A sample of each substrate was set aside at the time of potting to determine physical properties. Substrate samples were packed in aluminum cores [7.6 cm (3 in) tall by 7.6 cm (3 in) i.d.] according to methods described by Fonteno and Bilderback (7). There were three replications for each substrate. Aluminum cores were attached to North Carolina State University Porometers™ (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, NC) for determination of air space (AS). Cores were weighed, oven dried for four days at 72C (162F), and weighed again to determine container capacity (CC). Total porosity (TP) was calculated as the sum of AS and CC. Bulk density (D_b) was determined using oven dried substrate in Al cores.

Substrate pH was measured using the pour-through procedure at 2, 4, and 8 weeks after potting (WAP). Recently matured foliage was harvested (12), rinsed with deionized water, then oven dried at 72C (162F) for 3 days. Samples were ground in a Tecator Cyclotec mill (Tecator AB, Hogenas, Sweden) through a 0.5 mm (0.02 in) screen. Foliar nitrogen (N) was determined with a Vario Max CN analyzer (Elementar Americas, Mt. Laurel, NJ). Other macronutrients and micronutrients were determined with a Thermo Iris Intrepid ICP-OES (Thermo Fisher Scientific, Waltham, MA). Shoot dry weight (SDW) was measured at the conclusion of the experiment (8 WAP).

There were eight single plant replications per treatment combination arranged in a completely randomized design. Data were subjected to analysis of variance (ANOVA), and repeated measures ANOVA where data were recorded more than once over time. Multivariate ANOVA was used to compare particle size distribution of the substrates, using Wilks' lambda as the test criterion. All statistical analyses were performed with SAS v. 9.1 (SAS Institute Inc., Cary, NC).

Experiment 2. This experiment was similar to Expt. 1, with the following exceptions. There were five substrate source materials including: switchgrass, miscanthus, willow chips, corn stover, and pine bark. Each material was amended with 20% sphagnum peat moss and 10% municipal solid waste compost (Groganix, Lake County Dept. of Utilities, Painesville, OH). Vinca were potted April 9, 2009, and averaged 9 cm (3.5 in) tall and 12 cm (4.7 in) wide at the time of potting. Data collected included particle size distribution of the hammermilled substrate materials (prior to amending with compost or peat); physical properties of the mixed substrates; substrate pH 2, 4, and 7 WAP; elemental analysis of plant foliage 7 WAP; and SDW at 7 WAP.

Results and Discussion

Experiment 1. Particle size distributions for the four substrates differed ($P < 0.0001$) (Table 1). Drzal et al. (5) and Puustjarvi and Robertson (13) separated soilless substrates into three classes; course [> 2.0 mm (0.08 in)], medium [0.5 to 2.0 mm (0.02 to 0.08 in)], and fine [< 0.5 mm (0.02 in)]. By this convention, switchgrass, willow chips, and corn stover had relatively similar percent of medium particles (55.3, 57.2, and 54.1%, respectively), while pine bark had less with 40.8% medium particles. Of the biofuel-based materials, switchgrass had a far greater portion of fine particles (39.9%) than coarse particles (4.8%). Corn stover was similar in this respect, although there was less disparity with 28.4% fine particles and 17.4% coarse. Willow chips, however, had fewer fine particles (16.2%) than coarse particles (26.6%).

Each of the measured physical properties was affected by substrate type or peat moss amendment, but not their interaction (Table 2). Regardless of peat moss rate, each of the biofuel-based substrates had higher AS than pine bark. Across all substrates, adding peat moss decreased AS from 49 to 43%. Container capacity for corn stover substrate was lower than all other substrates, with or without peat moss. All other substrates had similar CC. Addition of peat moss increased CC across all substrates from 37 to 43%. Peat moss similarly decreased AS and increased CC in Douglas fir bark substrates (16). Total porosity was higher for biofuel-based substrates than pine bark. Peat moss had no effect on TP, presumably because TP is calculated as the sum of AS and CC and the opposing effect that peat moss had on AS and CC resulted in no net change of TP. Bulk density for biofuel-based substrates was lower than pine bark. Across all substrates, peat moss decreased D_b slightly.

Repeated measures analysis of substrate pH indicated a significant time by substrate and time by peat moss interaction ($P = 0.0001$ for both), but not a three-way interaction ($P = 0.2132$). Substrate pH of pine bark was 4.0 to 4.5 throughout the experiment, regardless of peat amendment (Table 2). Biofuel-based substrates with no peat amendment had a relatively high pH, ranging from 6.8 to 7.4. Although pH requirement varies by crop, these values are 1 to 1.5 units higher than what is typically considered optimum (15). Amendment of biofuel-based substrates with peat moss reduced pH by 1.0 unit across all substrates and time. Peat moss pH used in this

Table 1. **Particle size distribution of biofuel plant materials after being processed through a hammermill with 0.95 cm screeen (n = 3) for Expts. 1 and 2.**

Particle size grouping	Seive size	Expt. 1 Switch-grass[z]	Expt. 1 Willow chip	Expt. 1 Corn stover	Expt. 1 Pine bark[y]	Expt. 2 Switch-grass	Expt. 2 Willow chip	Expt. 2 Corn stover	Expt. 2 Miscanthus	Expt. 2 Pine bark
	(mm)	%								
Fine particles	Pan	2.7	0.6	1.9	2.7	2.4	0.4	1.9	1.3	1.5
	0.1	2.9	1.1	1.5	2.5	5.3	0.9	1.0	1.2	1.9
	0.2	3.7	1.3	1.6	2.3	7.1	1.0	1.0	1.2	2.0
	0.3	7.4	2.4	3.5	3.3	10.8	1.9	2.5	2.8	3.8
	0.4	10.7	3.7	6.6	4.0	12.6	2.3	6.0	4.6	5.4
	0.5	12.4	7.0	13.3	5.6	13.6	4.3	12.9	8.3	8.1
Medium particles	0.7	12.0	7.7	11.6	6.9	9.6	4.1	11.2	10.0	9.4
	1.0	14.0	10.8	12.1	8.5	12.7	5.8	12.6	14.1	9.5
	1.4	18.9	17.8	16.1	13.0	16.6	10.2	15.9	19.7	12.7
	2.0	10.4	21.0	14.4	12.3	7.7	17.8	15.6	16.6	12.0
Coarse particles	2.8	3.8	20.8	13.4	14.4	1.3	32.1	13.8	12.0	14.3
	4.0	0.9	5.6	3.6	16.2	0.2	17.8	5.1	5.9	14.6
	6.3	0.1	0.2	0.3	8.3	0.0	1.1	0.5	2.0	4.7
	12.5	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.1	0.0

[z]Switchgrass (*Panicum virgatum*), corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus* ×*giganteus*) were stored as dry bales prior to processing through a hammermill. Willow (*Salix* spp.) chips were stored fresh in a Gaylord box.

[y]Pine bark was not processed through a hammermill, but used in the form made avaialable by Fafard.

experiment was 4.5. The ability of relatively low volumes of peat moss to reduce pH of biofuel-based substrates suggests these substrates have little buffering capacity to resist change in pH. A similar conclusion was made with respect to limited buffering of switchgrass to changes in pH from irrigation water and fertilizer solution (1).

Tissue analyses showed that foliar N, potassium (K), sulfur (S), boron (B), manganese (Mn), copper (Cu), and zinc (Zn) were within the ranges listed by Mills and Jones (12) as being adequate for annual vinca (Table 3). Only vinca growing in corn stover (not amended with peat moss) had less than recommended phosphorus (P), however, all other treatments had levels near the low end of the adequate range. Although there were no visual deficiency symptoms, there were low Ca and Mg concentrations in tissue analyses for all substrates, except those comprised of willow chips, and this was likely due to lack of a lime source. Historically, lime has been an important source for substrate Ca and Mg (depending on lime

Table 2. **Physical properties, substrate pH, and shoot dry weight (SDW) of annual vinca (*Catharanthus roseus* 'Pacifica Blush') growing in substrates composed of ground biofuel materials after being processed through a hammermill with 0.95 cm screeen and amended with 0 or 20% peat moss (v/v) in Expt. 1.**

Substrate[z]	Peat moss	Air space	Container capacity	Total porosity	Bulk density	Substrate pH 2 WAP[y]	Substrate pH 4 WAP	Substrate pH 8 WAP	Shoot dry weight
	(%)	%			(g/cm^3)				(g)
Switchgrass	0	51	39	91	0.08	7.4	7.3	6.8	4.3
Willow chip		50	38	87	0.10	6.8	7.1	7.2	2.4
Corn stover		57	31	87	0.05	6.9	7.1	7.1	2.1
Pine bark		39	40	79	0.15	4.1	4.2	4.1	3.6
Switchgrass	20	45	45	89	0.07	6.2	6.4	6.1	3.1
Willow chip		41	45	86	0.09	5.6	6.2	6.4	3.7
Corn stover		52	38	89	0.05	5.6	6.2	6.1	3.0
Pine bark		33	47	80	0.15	4.0	4.1	4.5	3.8
$LSD_{0.05}$		6	6	2	0.01	0.2	0.1	0.3	1.2
Main effects									
Substrate		0.0001	0.0012	0.0001	0.0001	0.0001	0.0001	0.0001	0.0197
Peat moss		0.0005	0.0002	0.6508	0.0141	0.0001	0.0001	0.0001	0.2675
Interaction		0.8503	0.9534	0.0576	0.7150	0.0001	0.0001	0.0001	0.0238

[z]Switchgrass (*Panicum virgatum*), willow (*Salix* spp.) chips, corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus* ×*giganteus*) were processed through a hammermill equipped with a 0.95 cm (0.375 in) screen.

[y]Weeks after potting.

Table 3. Foliar nutrition levels in annual vinca (*Catharanthus roseus* 'Pacifica Blush') grown in various alternative substrates amended with or without peat moss in Expts. 1 and 2.

Experiment	Substrate[z]	Peat	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Si
		(%)	%						mg·kg^{-1}					
1	Switchgrass	0	4.6	0.42	2.6	0.84	0.25	0.35	36.1	74.9	203.2	9.2	45.9	131.2
	Willow chip		4.3	0.33	3.0	1.09	0.21	0.31	30.9	71.3	154.6	9.0	67.2	141.1
	Corn stover		3.6	0.23	2.4	0.67	0.21	0.28	32.2	44.0	155.4	7.2	43.9	161.3
	Pine bark		5.0	0.36	2.9	0.68	0.24	0.36	30.3	61.5	406.2	8.8	61.0	124.5
	Switchgrass	20	4.6	0.34	2.7	0.72	0.24	0.32	29.0	77.7	209.9	9.9	53.9	123.1
	Willow chip		4.2	0.32	2.6	1.04	0.21	0.33	35.9	69.4	267.3	10.5	70.4	115.2
	Corn stover		4.5	0.33	2.7	0.66	0.24	0.32	32.4	58.4	214.5	8.9	55.8	119.1
	Pine bark		4.2	0.30	2.5	0.62	0.23	0.29	34.0	54.7	306.0	6.9	53.3	125.5
	$LSD_{0.05}$		0.7	0.10	0.5	0.13	0.05	0.06	7.6	23.1	55.4	1.9	13.0	24.8
	Main effects													
	Substrate		0.3695	0.0436	0.6109	0.0001	0.1528	0.3883	0.9653	0.0137	0.0001	0.0098	0.0002	0.3075
	Peat		0.9132	0.6617	0.3094	0.0568	0.8473	0.6081	0.8304	0.7122	0.1600	0.2981	0.2358	0.0037
	Interaction		0.0019	0.0634	0.1766	0.5675	0.5393	0.0985	0.1244	0.6052	0.0001	0.0346	0.1827	0.0804
2	Switchgrass	20[y]	4.2	0.38	2.1	0.89	0.34	0.33	105.2	68.8	198.2	6.8	63.7	95.9
	Willow chip		4.1	0.42	2.1	0.96	0.31	0.31	113.1	65.6	170.5	6.7	67.1	75.7
	Corn stover		4.1	0.39	2.1	0.85	0.37	0.31	98.7	66.7	193.2	6.1	67.4	95.0
	Miscanthus		4.0	0.36	2.1	0.78	0.28	0.32	105.6	86.9	192.1	7.9	65.5	127.4
	Pine bark		4.0	0.36	1.9	0.82	0.34	0.33	83.9	67.9	257.9	5.9	74.4	87.3
	$LSD_{0.05}$		NS	NS	NS	0.10	0.03	NS	NS	17.0	32.6	1.7	NS	19.4
Adequate range[x]			2.7–6.3	0.28–0.64	1.88–3.48	0.93–1.13	0.32–0.78	0.22–0.5	21–49	72–277	135–302	6–16	30–51	

[z]Switchgrass (*Panicum virgatum*), willow (*Salix* spp.) chips, corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus* ×*giganteus*) were processed through a hammermill equipped with a 0.95 cm (0.375 in) screen.

[y]Substrates in Expt. 2 were amended with 10% municipal solid waste compost and 20% sphagnum peat moss (v/v).

[x]Mills, H.A. and J.B. Jones. 1996. Plant Analysis Handbook II. MicroMacro Publishing. Athens, GA.

Table 4. **Physical properties, substrate pH, and shoot dry weight (SDW) of annual vinca (*Catharanthus roseus* 'Pacifica Blush') growing in substrates composed of ground biofuel materials after being processed through a hammermill with 0.95 cm screen and amended with 10% municipal solid waste compost and 20% sphagnum peat moss (v/v) in Expt. 2.**

Substrate[z] parent material	Air space	Container capacity	Total porosity	Bulk density	Substrate pH 2 WAP[y]	4 WAP	7 WAP	SDW[x]
	%			($g \cdot cm^{-3}$)				(g)
Switchgrass	28	61	88	0.10	5.3	6.0	6.3	8.4
Willow chips	41	48	89	0.11	5.1	6.0	6.5	6.2
Corn stover	42	44	86	0.06	5.1	5.8	6.6	7.3
Miscanthus	58	34	93	0.07	5.1	5.6	6.1	6.6
Pine bark	19	60	79	0.17	4.2	4.7	5.2	10.2
$LSD_{0.05}$	8	8	2	0.01	0.2	0.3	0.7	1.4

[z]Switchgrass (*Panicum virgatum*), willow (*Salix* spp.) chips, corn (*Zea mays*) stover, and giant miscanthus (*Miscanthus* ×*giganteus*) were processed through a hammermill equipped with a 0.95 cm (0.375 in) screen.

[y]Weeks after potting.

[x]Shoot dry weight.

type) in pine bark substrates. Because pH of biofuel-based substrates are near neutral or alkaline, lime will not likely be needed or recommended for pH adjustment. Calcium and Mg are a component of the micronutrient fertilizer package used in these experiments (5 and 3% by weight, respectively), however, when applied at the recommended rates, amounts of applied Ca and Mg were minimal compared to that provided by typical lime applications. Foliar iron (Fe) levels were at or below the low end of the sufficiency range for annual vinca. Although all substrates were amended with a micronutrient fertilizer package, either the levels provided were insufficient to provide adequate Fe or substrate pH was not the range to render Fe cations available for plant uptake.

Vinca shoot weight was affected by an interaction between substrate type and peat amendment rate (Table 2). Vinca grown in pine bark without peat moss had higher shoot dry weight than those grown in corn stover and willow chip substrates, but had similar growth (although numerically less) to those grown in switchgrass substrate. In contrast, vinca grown in pine bark with peat moss had similar growth to all other peat moss-amended substrates.

Experiment 2. Multivariate analysis of variance indicated a significant treatment effect on particle size distribution of substrates (P = 0.0048) (Table 1). Switchgrass, corn stover, and pine bark followed a similar trend to Expt. 1 with respect to fine, medium, and coarse particles. Willow chips differed in this experiment relative to the previous experiment with a greater portion of coarse particles (51.2%) compared to medium particles (38.0%). Miscanthus was composed primarily of medium particles (60.4%) and a similar portion of fine (19.6%) and coarse (20.0%) particles. We initially thought that miscanthus would behave similarly to switchgrass in terms of processing and handling. At the time materials were ground through the hammermill, miscanthus and switchgrass had 8 and 32% moisture content, respectively. We observed with the hammermill used in this research, that dry materials flow through the screen more readily than moist materials. Moist materials tend to clog some holes in the screen, causing greater residency time for the remainder of the material in the hammermill chamber where particle size is further reduced. The overall result is that for any give material, greater moisture content will result in longer grinding time and a greater proportion of fine particles.

The ideal AS range for nursery substrates is thought to be 10 to 30% (15). By this standard, switchgrass and pine bark substrates had acceptable AS (Table 4). Willow chips and corn stover substrates had similar AS (41 and 42%, respectively); while miscanthus substrate had extremely high AS (58%). Container capacity was similar for pine bark and switchgrass substrates, and within the ideal range of 45 to 65% (15). Willow chips and corn stover substrates had similar CC, and near the lower limit of the ideal range. Miscanthus substrate CC was well below what is considered ideal for container nursery crops. Total porosity of pine bark substrate was lower and bulk density higher than that for all biofuel-based substrates.

Pine bark substrate pH at 2 WAP was lower than other biofuel substrates (Table 4). Switchgrass substrate pH was slightly, though significantly, higher than willow chip, corn stover, or miscanthus substrates. Repeated measures analysis indicated a significant time effect (P = 0.0001) but no interaction between time and substrate type (P = 0.4929). Over time, substrate pH averaged across substrate types increased from 4.9 to 5.6, then to 6.1. By 7 WAP, pine bark substrate still had the lowest pH, with all biofuel-based substrates having similar pH. In Expt. 1 substrate pH of those amended with peat moss also increased over the course of the study. Substrate pH for vinca is recommended to be 5.5 to 6.0, with pH above 6.5 being undesirable due to potential for Fe deficiency (9). Across both experiments, biofuel-based substrates approached this limit after 7 or 8 weeks of production. Longer term experiments are needed to determine if increase in substrate pH would continue or stabilize.

Foliar N, P, K, B, S, and Zn were not affected by substrate type (Table 3) and all were within adequate ranges (12). Similar to Expt. 1, foliar Ca and Mg were at or below the adequate range for plants growing in all substrates. This is likely due to the omission of lime. Vinca growing in miscanthus substrate had higher foliar Fe levels than other plants, and were the only plants with adequate foliar Fe. Vinca growing in pine bark substrate had the highest foliar Mn levels, but all vinca were within the adequate range for this nutrient. Foliar Cu levels were at or near the adequacy range, with plants growing in miscanthus substrate having the highest levels.

Vinca SDW was greatest in pine bark substrate (Table 4). Among the biofuel-based substrates, plants growing in switchgrass substrate had the greatest SDW (although statistically similar to corn stover). This differs from Expt. 1 where all plants were of similar SDW when grown in substrates amended with peat moss. Plants had greater SDW in this experiment compared to the previous, and thus growth differences would have manifested more readily. Greater overall SDW in this experiment is likely due to the size of plants at the time of potting (larger in Expt. 2) and the time of year the experiment was conducted.

Others have shown successful utilization of wood and grass-based materials in substrates. Kresten Jensen et al. (10) reported that English ivy (*Hedera helix*) grew well in composted miscanthus (*Miscanthus ogiformis*) substrates, although dry matter accumulation was greater in peat-based substrates. Handreck and Black (8), presumably speaking from experience with hardwood tree species of Australia, recommend that all hardwood sawdusts or wood chips be composted prior to use in substrates due to their propensity for immobilizing N. However, Brown and Duke (3) showed that melaleuca (*Melaleuca quinquenervia*) constituting up to 35% of container volume provided excellent growth and development of hibiscus (*Hibiscus rosa-sinensis*) and pittosporum (*Pittosporum tobira*). Conover and Poole (4) similarly showed melaleuca wood to provide a suitable substrate for aglaonema (*Aglaonema cummutatum*) and nephrolepis (*Nephrolepis exaltata*).

More research will be focused on amendment of biofuel-based substrate, such that they possess physical and chemical properties closer to ideal ranges. Based on data presented herein, biofuel-based substrates alone do not provide physical properties considered ideal for container crops. Air space is too high and container capacity is too low. Substrates derived from biofuel crops also have substrate pH 1.0 to 1.5 units higher than what is often considered ideal. Amending these substrates with 20% sphagnum peat moss and 10% municipal solid waste compost (v/v) adjusts physical properties so that they are within the ideal ranges and lowers substrate pH. Foliar nutrient content of annual vinca growing in biofuel-based substrates had lower than ideal foliar Ca, Mg, and Fe, although these nutrients are easy to correct with common fertilizer supplements. The propensity of these materials to decompose or disintegrate during longer production cycles is a concern, and is currently being evaluated.

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