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Pelleted biochar: Chemical and physical properties show potential use as a substrate in container nurseries

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ABSTRACT

We found that peat moss, amended with various ratios of pellets comprised of equal proportions of biochar and wood flour, generally had chemical and physical properties suitable for service as a substrate during nursery production of plants. High ratios of pellets to peat (>50%) may be less desirable because of high C:N, high bulk density, swelling associated with water absorption, and low volumetric water content, whereas a mixture of 75% peat and 25% pellets had enhanced hydraulic conductivity and greater water availability at lower (<−10 kPa) matric potentials. Adding pellets to substrates used to grow plants in nurseries has potential to add value to biochar and thereby improve economic viability of pyrolysis. Moreover, biochar-amended substrates offer opportunity to sequester carbon as part of the normal outplanting process.

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1. Introduction

Pyrolysis is the process of heating a biomass feedstock rapidly in the absence of oxygen, and then quickly condensing the resultant vapors into bio-oil, the desired product [1]. The residue is biochar, a granular, carbon-rich substance. Its particulate form reduces microbial decomposition so biochar persists in the environment. Intuitively, generating the highest-value target products and adding value to residual products are both essential for sustainable biomass conversion to energy [2,3]; adding value to residual biochar would improve the overall economic efficiency of pyrolysis.

Biochar has potential value. It can be used to filter pyrolysis exhaust gases [4], serve as base product for production of nitrogen fertilizer [5], be treated with steam to generate activated carbon [6], and has been suggested as a farm fertilizer [4,7] and as a way to improve forest productivity [8]. As a soil amendment, biochar can increase water-holding capacity, reduce bulk density, provide additional cation exchange sites, and serve as a source of reduced carbon compounds that may benefit microbial populations [7,9–13], all of which promote plant growth.

These potential benefits to plant growth may be leveraged in the nursery production of plants, particularly for those grown in small volume (<500 ml) containers for reforestation and ecosystem restoration [14]. Unfortunately, chemical and physical properties of substrates in containers, which are primarily organic in nature and influenced by the dynamics of the containers themselves, behave much differently than mineral soils found on farms and in forests [14]. Although

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high-quality *Sphagnum* peat has the requisite attributes, such as low pH, high cation exchange capacity (CEC), low inherent fertility, a proper balance of aeration and water-holding porosity, and sufficient rigidity to support the plant to be used alone [14–17], in the United States it is often mixed with inorganic amendments to reduce costs or provide other benefits [14]. Costs of some commonly used amendments, such as vermiculite, have risen more than 50% since 2004; this, combined with growers' interest in making use of locally-available, environmentally-friendly products has led growers to examine other amendments [18]. Therefore, biochar may be an excellent amendment in nursery substrates except that dustiness of the material is a nuisance [19], and it is very fine-textured and subsequently difficult to incorporate evenly for use in small volume containers [14,20,21]. Pelleted biochar would be easier to handle, and the larger size of pellets may improve total porosity and aeration porosity in containers, highly desired attributes [14,22,23] and their proper balance is essential for optimum seedling growth [16]. To our knowledge, this is the first report of creating biochar pellets for nursery use.

Although we present details on our pellet production method, our primary objective was to evaluate the chemical and physical properties of biochar processed into pellets and mixed as an amendment with *Sphagnum* peat to form five distinct growing media. Our goal was to assess combinations of peat and pellets for potential use in container nurseries.

2. Materials and methods

2.1. *Pellet components and formation*

We dry blended, on a weight basis, 43% biochar, 43% wood flour, 7% polylactic acid, and 7% starch in a ribbon mixer (Scott Equipment Co., New Prague, MN, USA) for 5 min. The biochar (Dynamotive Energy Systems Corporation, Richmond, BC, Canada) was residual material from pyrolysis (cellulosic biomass from agricultural or forestry residues having <10% moisture by mass and 1–2 mm particle size heated to 450–500 °C; [24]). Wood flour was finely-ground (60-mesh) *Pinus strobus* having 6–9% moisture content (American Wood Fibers, Schofield, WI, USA). Binders included polylactic acid (PLA-PR-NAT 2002D; Jamplast Inc., Ellisville, MO, USA) and wheat starch (Edigel® 100, Archer Daniels Midland Co., Decatur, IL, USA). Attempts to pelletize biochar using the binders (polylactic acid and wheat starch) without wood flour failed to yield a cohesive pellet. We measured the particle distribution of each component using a series of sieves (0.5 mm–5 mm).

Blended material was fed into a 100 hp commercial pellet mill (California Pellet Mill Co., Crawfordsville, IN, USA) fitted with a parabolic entry die with an overall length of 63.5 mm to extrude random length (4–25 mm) pellets with a 4.8 mm diameter. The die length included a relief section of 6.4 mm at the end of the die resulting in an output diameter of 5.4 mm.

By hand and on a volume basis, we combined pellets (PL) and peat (PE; fine-textured, non-fertilized horticultural grade without a wetting agent; Sunshine grower grade green, Sun Gro Horticulture Ltd., Canada) to form five distinct growing media (Table 1).

Table 1 – Ratios (v v^{-1}) of peat (PE) and biochar pellets (PL) for each of five growing media.

Growing media designation	Peat (%)	Pellet (%)
PE100PL0	100	0
PE75PL25	75	25
PE50PL50	50	50
PE25PL75	25	75
PE0PL100	0	100

2.2. *Growing media – physical assessment*

To measure water uptake and change of volume of the bale-dry growing media, we filled metal cylinders (height 60 mm, diameter 58 mm) with each media and placed them into water kept 5–10 mm deep (3 replications). Volumetric water content (VWC) at decreasing matric potentials (i.e., desorption water retention characteristics) of samples was measured using a pressure plate apparatus (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) and standard methods [25,26]. Similar metal cylinders were filled with each media, saturated, allowed to drain freely (to about −0.3 kPa), and then exposed to successive matric suctions of 1, 5, 10, 100, and 1500 kPa (5 replications). At each matric potential, water content was reassessed gravimetrically. We chose an initial suction of 1 kPa because this value reflects container capacity, the maximum plant available water retained by the container medium when allowed to freely drain from saturation [27,28].

We determined bulk density as the ratio of dry mass (dried at 105 °C) to saturated volume and estimated particle density using an average density of 2.65 g cm^{-3} for mineral and 1.5 g cm^{-3} for organic components. Organic matter content for peat, pellets, and the growing media was estimated by loss on ignition at 550 °C (5 replications).

Total porosity (TP) was estimated using:

$$TP = (Dp - Db)/Dp$$

where Dp is particle density and Db is bulk density of the material.

Air-filled porosity (AFP) was estimated using:

$$AFP = TP - VWC$$

where VWC is the volumetric water content at −1 kPa, assumed to be container capacity [27,28].

Oxygen gas diffusivity (Ds) in relation to that in free air (Do), i.e. relatively gas diffusivity (Ds/Do), was estimated as a function of AFP using fitted curves by Gislerod [29] and King and Smith [30].

We measured saturated hydraulic conductivity by applying the constant-head method [25,26]. To reduce the effect of varying temperature on the rate of water flow on hydraulic conductivity, we used the ratio of kinematic viscosity at the observed temperature to that at 10 °C [25] replicated twice. Unsaturated hydraulic conductivity was measured for PE100PL0, PE75PL25, and PE50PL50 using Ku-pF apparatus (UGT GmbH, Müncheberg, Germany), where sample cylinders (2 replications) were allowed to dry by evaporation at room temperature [31,32].

Table 2 – Mean particle size distribution (%) of the pellet components, intact pellets, and peat determined by dry sieving ($n = 3$).

Component	>5 mm	2–5 mm	1–2 mm	0.5–1 mm	<0.5 mm
Biochar	0.0	0.2	0.8	10.5	88.4
Wood flour	0.0	0.1	0.1	0.1	99.6
Polylactic acid	0.0	100.0	0.0	0.0	0.0
Starch	0.0	0.0	0.1	1.5	98.4
Pellets	19.2	65.9	4.3	2.7	8.0
Peat	0.9	16.7	31.6	19.3	31.5

2.3. *Growing media – chemical assessment*

Our measurements of total, soluble (easily extracted nutrients), and press water (nutrients residing in the soil solution) nutrient concentrations, as well as effective cation exchange capacity (total exchangeable nutrients based on select cations), were replicated five times. We measured total carbon (C) and nitrogen (N) from sieved and air-dried samples on a CHN analyzer (LECO-1000, LECO Corp., St. Joseph, MI, USA). Samples for other nutrients and elements were digested by the closed wet HNO_3–HCl digestion method in a microwave (CEM MDS-2000; CEM Corp., Matthews, NC, USA) and the extract was analyzed on a TJA Iris Advantage ICP-emission spectrometer (Thermo Jarrell Ash Corporation, Franklin, MA, USA).

To assess soluble nutrients, we wetted samples of each medium and incubated them for 1, 15, or 29 days at room temperature. Samples were remoistened about twice each week to mimic the wetting and drying cycles found under normal nursery cultural practices. For each sample date, acid ammonium acetate (pH 4.65) was used to gather soluble cations and easily soluble phosphorus (P). Cations in the filtered solution were quantified using an ICP atomic emission spectrometer (Thermo Jarrell Ash Corporation, Franklin, MA, USA). Soil ammonium (NH_4–N), nitrate (NO_3–N), and total N were determined from a KCl-extract on a FIA-analyzer (Lachat QuickChem 8000, Lachat Instruments, Milwaukee, WI, USA). Using a microwave (CEM MDS-2000; CEM Corp., Matthews, NC, USA), we used the hot water refluxing method to extract easily soluble boron and the extract was analyzed on the spectrometer described above.

To determine nutrients in a press water extract, we designed an apparatus consisting of a cylindrical chamber and a vertical piston that when deployed, delivered a constant 300 kPa pressure. After the incubation periods described above, we pressed each medium sample and the subsequent extracts were measured for pH and electrical conductivity, filtered, and analyzed (PE0PL100 yielded no press water extract) for dissolved major and trace elements on the spectrometer described above. Concentrations of dissolved NH_4–N, NO_3–N and dissolved total N were determined on the FIA-analyzer described above. Because our analysis of NO_3–N included NO_2–N, we estimated organic N (ON) using:

$$ON = N_{total} - NH_4 - N - NO_3 - N$$

For cation exchange capacity, substrates were prepared as described for soluble nutrients. We used a 0.1 M $BaCl_2$ solution to extract exchangeable cations. Once filtered, the total concentrations of exchangeable cations in the solution were determined on the spectrometer described above. To determine exchangeable acidity, the 0.1 M $BaCl_2$ extract was titrated with a 0.05 M NaOH solution up to pH 7.8. We calculated effective cation exchange capacity [ECEC(cmol kg^{-1})] using:

$$\mathrm{ECEC}\left(\mathrm{cmol\ kg^{-1}}\right) = \mathrm{Na}\left(\mathrm{cmol\ kg^{-1}}\right) + \mathrm{K}\left(\mathrm{cmol\ kg^{-1}}\right) + \mathrm{Ca}\left(\mathrm{cmol\ kg^{-1}}\right) + \mathrm{Mg}\left(\mathrm{cmol\ kg^{-1}}\right) + \mathrm{ACI\_E}\left(\mathrm{cmol\ kg^{-1}}\right)$$

where ACI_E is exchangeable acidity from $BaCl_2$ extract. We calculated percentage base saturation as the sum of the bases (Na, K, Ca, Mg) divided by ECEC.

2.4. *Statistical analyses*

We used the generalized linear mixed model (GLIMMIX) within SAS version 9.2 Software (SAS, Inc., Cary, NC, USA), accounting for the random effect of date in the analysis, to compare substrate means. We assumed a Gaussian response distribution and used the default covariance matrix format. Type III tests of fixed effects were used to examine main effects for each omnibus model.

3. Results

3.1. *Pellet components and peat*

Most of the raw biochar (88%), wood flour (100%), and starch (98%) had a particle size < 0.5 mm, whereas the polylactic acid

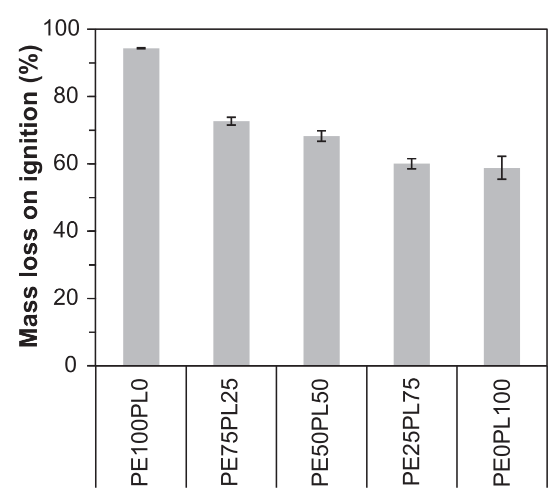

Fig. 1 – Loss on ignition of the growing media ($n = 5$) (mean ± Sd).

Table 3 – Total carbon, nitrogen, and the carbon-to-nitrogen ratio of pellet components, intact pellets, and peat ($n = 3$).

	C (%)	Total N (%)	C:N
Biochar	74.0	0.37	199
Wood flour	52.6	0.23	232
Polylactic acid	49.2	<0.06	>820
Starch	45.1	1.08	42
Peat	52.6	1.26	42
Pellet	58.9	0.23	254

beads were 2–5 mm in diameter (Table 2). Subsequent pellets, although 4.8 mm in diameter, exhibited a variety of lengths and therefore passed a variety of screen sizes (Table 2). Pellets remaining on the 5-mm sieve had an average length of 9.8 mm. The peat also had variable size, with the greatest proportions occurring in the 1–2 mm (32%) and <0.5 mm (32%) classes.

Bulk density (Db) of the peat and biochar was 0.092 and 0.2 Mg m^{-3}, respectively. Db increased with addition of pellets, with 25, 50, 75, and 100% pellets yielding 0.223, 0.387, 0.469, and 0.527 Mg m^{-3}, respectively; all values were significantly different ($P < 0.0001$) from each other. Nearly all peat was lost on ignition (94%) whereas only 44% of the biochar pellet was lost. Subsequently, the amount of organic material lost through ignition from each mixture decreased with addition of biochar pellets (Fig. 1).

Total concentrations of N and C in peat and pellets were significantly different (both $P < 0.0001$). Peat had the lowest C:N (42). High C:N in wood flour (232) and biochar (199), the main components of pellets, led to a pellet C:N of 254, about 6X that of peat (Table 3). Total concentrations of other plant nutrients and heavy metals varied between the peat and pellets and were significantly different (all $P < 0.0001$) except for Cd and Pb; Cd levels were below the detectable limit for both and Pb levels were similar ($P = 0.9002$) (Table 4). Peat had 10X, 2X, 3X, 2X, and 13X more Al, Ca, Mg, P, and S than the pellets, whereas pellets had 2X, 66X, 2.5X, 5X, and 3X more B, Cr, Cu, K, Ni than the peat.

3.2. *Growing media – physical assessment*

Upon initial exposure to water, all five growing media adsorbed water (Fig. 2a). During the first 5 min, media having ≥50% peat achieved a VWC of about 22%, about a third greater than PE25PL75 (16%) and nearly twice that of PE0PL100 (10%). After 50 min, VWC for PE50PL50 was highest (55%), followed by PE75PL25 (42%), PE100PL0 (39%), PE25PL75 (37%), and PE0PL100 (21%). After 24 h of exposure, VWC for PE75PL25 and PE50PL50 were the highest and similar (70%), followed by PE100PL0 (66%), PE25PL75 (62%), and PE0PL100 (37%).

Water moved readily at the highest matric potential for the PE75PL25 mixture, with prevalent, consistent movement of about 1 cm day^{-1} beginning at −0.3 kPa, before dropping when potentials were lower than −1 kPa (Fig. 2b). Conductivity of water through pure peat (PE100PL0) also occurred at the highest potential but rate of movement was more variable than PE75PL25 and did not decline significantly until matric potential dropped to −10 kPa. For PE50PL50, a matric potential of nearly −3 kPa was necessary to initiate water movement, and although rate of movement was initially high, the rate dropped quickly with minor lowering of potential. During this initial adsorption of water, the volume of the growing media with ≥50% peat shrank, whereas those with ≥50% pellets expanded (Fig. 3). Pure peat, PE100PL0, had the most shrinkage (12%) and pure pellets, PE0PL100, expanded the most (27%).

Total porosity decreased with increasing additions of pellets (Fig. 4); porosity was highest in pure peat (PE100PL0;

Table 4 – Total element concentrations (mg kg^{-1}) in pellet components, intact pellets, and peat prior to mixing the growing media ($n = 3$); soluble nutrients (mg kg^{-1}) in each growing media after 29 days of moist incubation ($n = 5$); and elements in the soil solution extract (mg l^{-1}) of each growing media after 29 days of moist incubation ($n = 5$).

	Al	B	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn
Total																	
Biochar	163.6	17.02	4694	<0.117	98.42	7.97	1108.0	4340	509.2	139.4	<1.2	81.5	10.75	178.6	3.35	117.4	15.72
Wood flour	20.8	3.27	803	<0.117	<0.22	1.40	11.8	494	150.2	34.48	<1.2	101.7	<0.22	36.6	<1.60	66.1	8.70
Polylactic acid	<17.7	<0.41	4	<0.117	<0.22	0.72	1.0	<62.1	0.4	<0.10	<1.2	20.4	<0.22	<4.35	<1.60	14.7	0.75
Starch	<17.7	0.67	561	<0.117	<0.22	3.06	30.7	923.6	376.4	21.74	<1.2	436.0	<0.22	1996.0	<1.60	744.6	17.90
Peat	1071.0	5.23	6162	<0.117	1.54	2.31	1698.0	469	1001.2	130	<1.2	81.3	1.86	542.8	2.47	1826.0	23.42
Pellet	93.1	10.56	2642	<0.117	98.66	5.84	1168.0	2540	363.4	98.34	<1.2	147.8	5.21	276.8	2.58	139.8	18.06
Soluble																	
PE100PL0	31.5	2.96	4954	–	–	–	11.3	350	873.6	131.80	–	–	–	71.6	–	245.2	–
PE75PL25	20.3	5.65	2492	–	–	–	11.8	1408	359.6	66.76	–	–	–	87.1	–	109.2	–
PE50PL50	17.4	6.23	1964	–	–	–	14.6	1680	266.6	56.80	–	–	–	98.7	–	72.2	–
PE25PL75	12.8	6.20	1456	–	–	–	31.9	1690	190.8	46.16	–	–	–	106.2	–	48.8	–
PE0PL100	5.1	6.17	1186	–	–	–	48.3	1590	137.4	38.86	–	–	–	108.4	–	56.7	–
Press water extract																	
PE100PL0	0.41	0.06	18	<0.001	0.01	<0.004	0.5	11	5.6	0.54	–	5.4	<0.010	3.2	<0.015	24.4	0.03
PE75PL25	0.58	0.35	23	<0.001	0.04	0.01	2.7	135	5.3	0.61	–	16.0	0.01	16.0	<0.015	27.1	0.07
PE50PL50	1.75	0.57	53	<0.001	0.12	0.01	6.3	368	13.8	1.48	–	38.0	0.03	36.0	<0.015	28.1	0.18
PE25PL75	1.12	0.63	77	<0.001	0.11	0.01	6.9	430	20.3	2.28	–	40.8	0.04	30.2	<0.015	20.0	0.26
PE0PL100	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

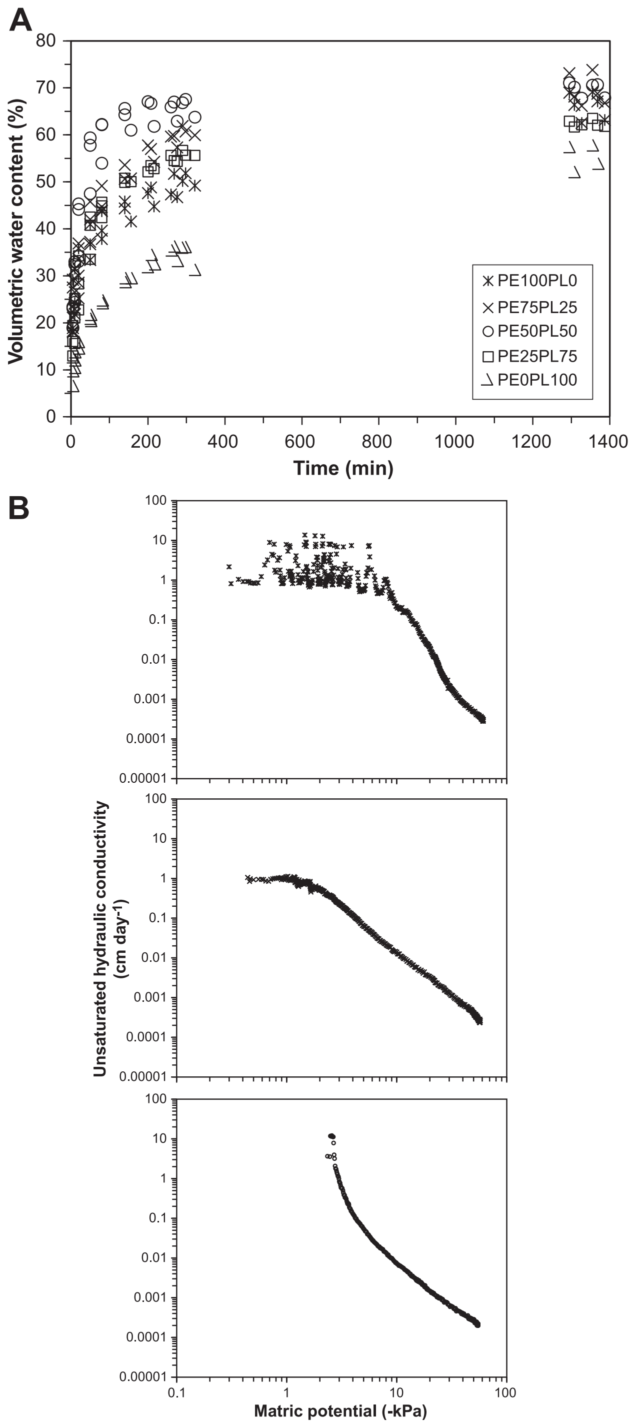

Fig. 2 – Wetting of the growing media in cylinders from below ($n = 3$); water content is expressed in relation to the initial bale-dry volume at the start (A). Unsaturaturated hydraulic conductivity ($n = 2$) (B); top, middle, and bottom panels for PE100, PE75PL25, and PE50PL50, respectively.

94%) and lowest in pure pellets (PE0PL100; 73%). Each media was significantly different ($P < 0.0001$). Porosity of all media near saturation (−0.3 kPa), except for the two media with the highest amounts of peat (PE100PL0 and PE75PL25) that had similar VWC of 73–74%, were significantly different

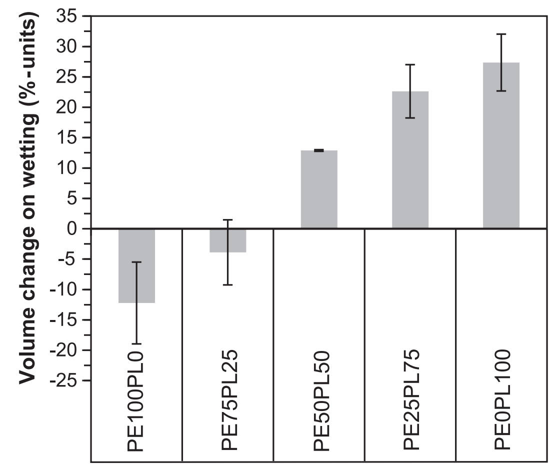

Fig. 3 – Change of bale-dry sample volumes during wetting in cylinders from below ($n = 3$) (mean ± Sd).

($P < 0.0001$): 50PE50PL (65%), PE25PL75 (51%), and PE0PL100 (46%). At −10 kPa, PE75PL25 retained the most water (44%), significantly ($P < 0.0001$) more than PE50PL50 (41%), PE100PL0 and PE25PL75 (34%), and PE0PL100 (31%).

Air-filled porosity at −1 kPa decreased when pellets were added to peat, but the decrease was not linear (Fig. 4). AFP was 47% for PE100PL0, significantly ($P < 0.0001$) greater than PE75PL25 (38%) which was significantly greater than PE50PL50

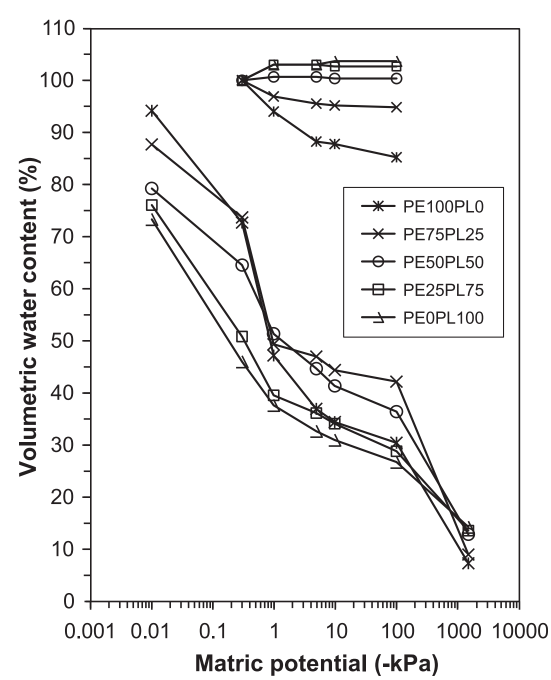

Fig. 4 – Mean desorption water retention characteristics of the growing media in relation to the initial wet volume (means of $n = 5$). The upper portion of the figure shows sample volumes in relation to the initial wet volumes (=100 %). An estimate of total porosity is plotted as water content at −0.01 kPa, with air-filled porosity determined as total porosity less VWC at each matric potential.

(28%). AFP for the lowest amounts of peat, PE25PL75 and PE0PL100, was, however, higher at 36% and not significantly different than the PE75PL25 mixture. Relative oxygen diffusivity through the media at either −1 or −5 kPa followed the same pattern as AFP (Fig. 5). Estimates obtained using King and Smith [30] were about half those of the Gislerod method [29], but followed the same pattern (data not shown).

3.3. Growing media – chemical assessment

Amounts of soluble NO_3, NH_4, and total N were greatest in the pure peat media for all three sample times; on day 1 total N from PE100PL0 was about 3X that of any media containing pellets. From day 1 through day 29, NO_3, NH_4, and total N decreased in PE100PL0 by 50%, 64%, and 75% respectively, and in general, the remaining media followed a similar pattern (Fig. 6). In the press water extracts, ON was lowest for all three sample times with PE100PL0 (Fig. 7) and increased with increasing levels of pellets. In general, ON and total N were similar, indicating very little NO_3 and NH_4 were in the substrate solution, except for PE100PL0, where more than half of the observed N was in either the NO_3 or NH_4 form. Across sample times, ON and total N values were highest when pellet content was ≥50%. After 1 day of incubation, ON and total N in these growing media were 2.5X and 3X greater than media containing <50% pellets.

The pure peat we used had soluble levels of B, Ca, Fe, Mg, Mn, P, and Zn within the recommended ranges for growing *Pinus sylvestris* and *Picea abies* in Finland, whereas K and Cu were below [33]. Levels of soluble nutrients followed consistent patterns. Increasing levels of pellets corresponded to increasing amounts of Fe, K, Na, P, and B and decreasing levels of Al, Ca, Mg, Mn, and S (Table 3). The mg kg^{-1} of each nutrient was fairly stable among sample dates, so only the 29-day sample is presented (Table 3). We observed, however, two exceptions. First, from day 1 to day 29, Na levels increased more with an increasing proportion of peat; 71% for PE100PL0

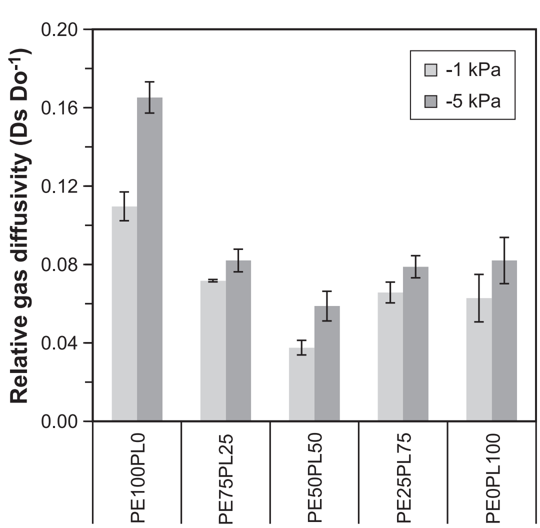

Fig. 5 – Mean relative oxygen gas diffusivity at −1 and −5 matric potentials according to Gislerod [29] (n = 3–5) (mean ± Sd).

(83–142 mg kg^{-1}) compared with 8% for PE0PL100 (118–128 mg kg^{-1}). Second, for the same period, S levels rose by nearly 50% in the PE100PL0 mix (166–245 mg kg^{-1}), but for the remaining media, the average percentage increase was about 108% (35–72 mg kg^{-1}). The quantities of nutrients in the press water extract (no water could be pressed from the PE0PL100 media) all followed the same pattern: nutrient levels increased with increasing amounts of pellets. Potassium levels were 10X higher when 25% of the peat was replaced with pellets, and 40X higher when 75% of the peat was replaced.

Average pH values across all three press water sampling times increased in alkalinity as the ratio of pellets went from zero to 75: 3.9, 4.4, 4.8, and 5.2, respectively. All media were significantly different from one another ($P < 0.0001$). Electrical conductivity of the growing media was fairly stable across the three sampling times, and followed a similar pattern as pH; 0, 25, 50, and 75% pellets yielded EC values of 0.30, 0.58, 1.15, and 1.37 Ms cm^{-1}. All media were significantly different from one another ($P < 0.0001$).

For effective cation exchange capacity and base saturation, the trends and values were quite similar across all three incubation dates, so only the 29-day values are provided (Table 3). ECEC was significantly different ($P < 0.0001$) for each growing medium, decreasing (44.6, 23.2, 17.9, 13.6, 10.7 cmol kg^{-1}) as the ratio of pellets increased (0, 25, 50, 75, 100%, respectively); reducing the volume of peat by 25% reduced ECEC by nearly 50%. When adjusted by volume, ECEC values were less linear; decreasing peat ratios from 100 to zero yielded ECEC values of 4014, 2904, 6552, 10670, and 5512 cmol m^{-3}, respectively. Conversely, base saturation, which was also significantly different ($P < 0.0001$) for each growing medium, increased (82.3, 88.0, 91.7, 93.8, 94.3%) as the ratio of peat decreased (100, 75, 50, 25, 0, respectively). Although peat had 3X the Ca and Mg than pellets, pellets had 5X and 2X more K and Na.

4. Discussion

A wide diversity of species are being grown for ecosystem restoration, and a variety of growing media in myriad container types are being used to produce them [34]. Ideal growing medium has characteristics that favor both seedling growth and efficient nursery operations [14]. Of the former, pH, CEC, inherent fertility, and porosity are critical, whereas cost, uniformity, ease of handling, bulk density, and dimensional stability are important for the latter.

4.1. Potential seedling growth

The pH of all tested media was lower than the 5.5 to 6.5 range recommended for most woody plants for restoration [14], with pure peat being the lowest (3.9); pH of our Sphagnum was typical [15]. Fortunately, most plants grow within a fairly wide range of pH if nutrients are supplied appropriately [15]; reforestation seedlings grown in Scandinavia are typically produced in a pure peat medium adjusted with dolomitic lime to achieve the recommended pH of 4.5–5.5 [33,35]. High cation exchange capacity is desired because it maintains a fertility

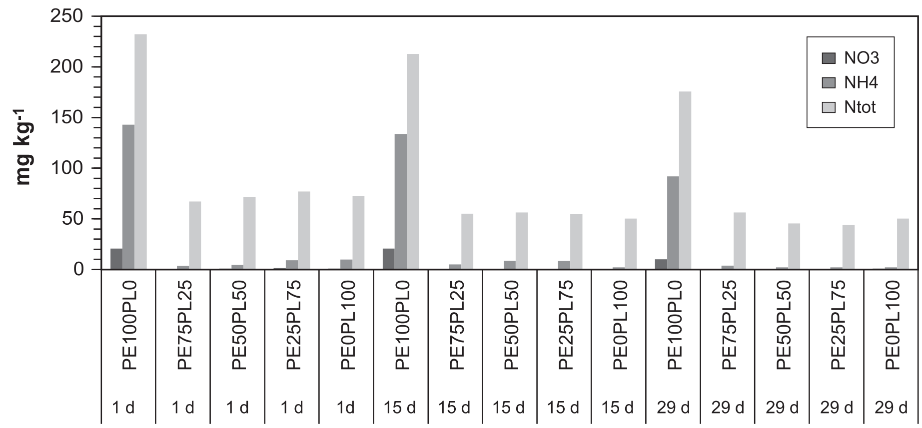

Fig. 6 – Soluble nitrogen in the growing media after 1, 15, and 29 days of incubation ($n = 5$).

reserve within the growing medium and helps mitigate leaching of nutrients during irrigation [14]. On a weight basis, adding pellets decreased ECEC, although leaching with a stronger or different leachate may affect results. On a volume basis, adding 25% pellets appears to reduce ECEC by about a third, but additional amounts of pellets indicate that biochar has an appreciable ECEC, greater than peat. Conversely, a greater volume of pellets increased base saturation, a function of Ca, Mg, K, and Na in the system. A higher base saturation generally indicates the potential for pH to increase during the growing season, which could mitigate our initial low pH values.

Growers desire low inherent fertility because they can then manipulate the nutrient pool as needed to control seedling growth. Our press water extracts revealed relatively low amounts of most nutrients in the soil solution across all media, with exception of K. In soil, most K moves slowly by diffusion, particularly in organic growing media, often requiring supplemental fertilization in container nurseries to ensure adequate levels in the plants [36]. Conversely, although K apparently has no direct toxicity effects, high K levels have caused Mg deficiency in *Pinus radiata* [37]. Therefore, the high K we observed is probably not a problem, and can be mitigated by prudent growers who routinely check foliar nutrient levels to ensure proper nutrition.

Pure peat had a moderate C:N (42:1) but replacing 25% of the peat with pellets increased C:N 100%. This higher C:N can be troublesome, as applied N in fertilizer will be immobilized by microorganisms and rendered unavailable for plant growth. High C:N can be mitigated, however, by incorporating additional N into the medium pre-planting at rates sufficient to meet microorganism demand [38], thus making all other applied N fertilization available to plants. A C:N ratio of 185 in a medium used to grow conifer seedlings was mitigated this way [39].

Adding a modest amount of pellets (25%) to peat had little effect on onset of unsaturated hydraulic conductivity, albeit flow rates were reduced, but that rate yielded more water at lower matric potentials (−1 to −100 kPa) than the other media. Even so, air-filled porosity at −1 kPa (container capacity) for the media ranged from 36 to 47% (except for the PE50PL50 medium at 28%), near the 40% optimum threshold suggested by Heiskanen [16].

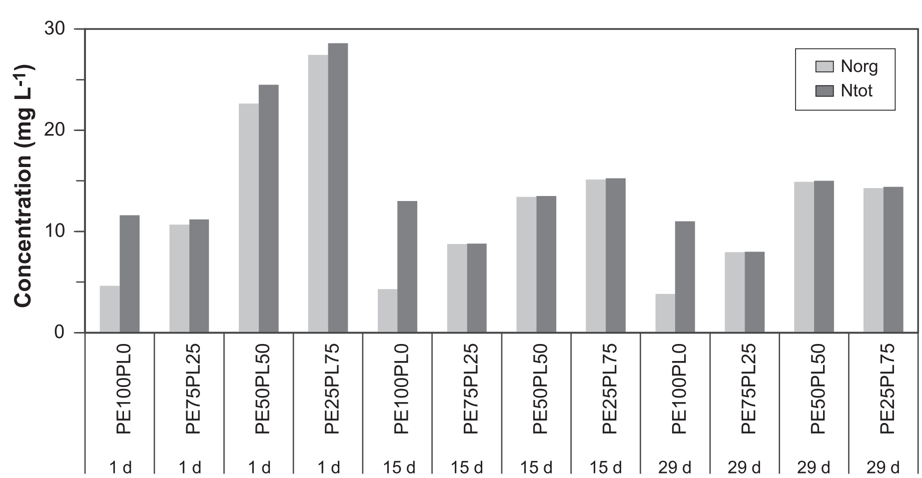

Fig. 7 – Organic and total nitrogen of press water extracts from the growing media after 1, 15, and 29 days of incuabation ($n = 5$).

4.2. Nursery operation considerations

Amendments, such as vermiculite, are commonly added to peat-based growing media used to produce native plants. Unfortunately, cost of amendments continues to increase. Growers are seeking less expensive alternatives, especially those produced locally [18]. Biochar may be such a product. Although our biochar was uniform in dimension, it was an extremely dusty, ashy material to work with. Pelletizing it reduced that disadvantage. Addition of biochar to peat dramatically increased bulk density, with pure pellets having 5X the density of pure peat. Higher rates of pellets increased substrate weight, which could have costly ramifications for handling, shipping, and outplanting. High bulk density may be an advantage, however, for plants grown in large containers outdoors, as the additional weight may improve stability of free-standing products. Perhaps of greater concern is the change in dimensional stability. Pure peat shrank by 15%, which can affect volumetric water content and must be adjusted for during the crop cycle. Conversely, pellets expanded nearly 30%, which could pose a problem in small volume containers; machine-filled containers may lack capacity to absorb that much expansion. The result may be media exuding out of the container, or severe within-container compaction that restricts root growth. The most important characteristic, however, is the response of the plant to each media and the formation of a proper root plug that facilitates outplanting and yields high survival, which can only be determined by growing different crops in the media.

4.3. Opportunities to improve pellets

We believe that pellets can be modified to improve results. Subsequent to this research, we observed that adding canola oil (Wesson®; ConAgra Foods, Inc., Omaha, NE, USA) at a 3% rate to the biochar/wood blend improved the rheology of the blend, which allowed for an improved pellet output rate and integrity. We believe, however, that more fundamental changes may enhance the product for nursery use. Most pellet research focuses on densifying pellets to obtain higher packing efficiencies, increased thermal capacity, etc. [40–42]. As a soil amendment for growing media in nursery operations, however, a less dense pellet may be more desirable, which could ameliorate the high swelling coefficients that we observed. Moreover, reduced pressures during formation should better maintain biochar porosity, important for optimum biological and chemical function [19]. Utilizing a larger die diameter and reducing die length could reduce pellet density, and subsequent potential problems with poorer pellet integrity and creation of fines could be addressed by adjusting polymer types and levels.

Improved media performance can also be obtained through formulation design. We added starch and PLA to achieve pellet integrity, but other biopolymers that may degrade more rapidly or slowly, could be used depending upon consumer preference. These formulations could provide more resistance to the internal stresses developed during water sorption and swelling. Such designer pellets could be amended with nutrients to further enhance pellet performance.

4.4. Potential carbon sequestration

Using biochar during nursery production has another potential advantage: an efficient way to achieve long-term, below ground C sequestration at little or no additional cost. McCarl et al. [2] cite transporting biochar and incorporating it into agricultural fields as a costly constraint. Once added to nursery growing media, however, biochar becomes part of the root plug already destined to be outplanted. Thus, the transportation and burial costs are already included *de facto*, although both costs may be slightly higher than traditional stock because of the additional bulk density of the material. Assuming: (1) 300 million container plants for reforestation and conservation planting in the Pacific Northwest USA and British Columbia, Canada; (2) an average container volume of 160 ml^3; (3) a 3:1 peat:pellet mixture (where 43% of the pellet is biochar and 74% of biochar is C); and (4), an average biochar Db of 300 $kg\,m^{-3}$ [24], a modest 1200 tonnes of C could be sequestered annually. Considering that reforestation and conservation container seedlings are a minuscule portion of the horticulture landscape business, the potential for burying C through outplanting ornamental plants, routinely grown in much larger volume containers, could be substantial.

4.5. Summary

We added biochar-based pellets to pure peat and assessed different ratios for potential use in nurseries. From our results, we speculate that a PE75PL25 may be appropriate for use in nurseries using small volume containers. Among substrates, this ratio improved hydraulic conductivity and yielded more water at high matric potentials (>-10 kPa) while retaining a desired 40% air-filled porosity. Although pellets increase Db and expand by 30% when wetted, adding 25% pellets nearly offset shrinkage (which affects volumetric water content over time) observed in pure peat. The greater expansions noted with pellet additions $\geq$50% will probably increase Db to unacceptable levels and/or cause problems with filling containers properly. Despite a lower ECEC on a weight basis with the addition of pellets as compared to pure peat, those pellets and their higher base saturation would tend to mitigate initial low pH values associated with pure peat. The higher C:N of any peat:biochar substrate, even at the PE75PL25 ratio, however, remains a concern. Opportunities exist to modify pellets to reduce pellet expansion and improve C:N. Finally, amending usual nursery substrates with biochar may offer an opportunity for low-cost carbon sequestration.

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