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Physicochemical Properties of Cattail (*Typha*) Bioproducts as Substitutes for Commercial Horticultural Growing Media

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Peat moss is a primary component of horticultural potting mixes, but its extraction is destructive to boreal bogs and results in considerable greenhouse gas emissions. In this study, we conduct a preliminary investigation into whether a suitable alternative could be produced from *Typha domingensis*. Cattail harvest offers a means to recycle nutrients from eutrophic wetlands but rarely occurs due to a paucity of economically viable uses. This study investigates *Typha*-derived bioproducts that could serve as peat substitutes, thus replacing a product that degrades wetlands with one that benefits them. Horticulturally relevant physical characteristics (water holding capacity, dry bulk density, and particle size distribution) and chemical characteristics (nitrogen [N] immobilization, pH, and conductivity) were compared for 3 *Typha* bioproducts (shredded *Typha*, *Typha* compost, and *Typha* biochar), a blend consisting of equal parts of these bioproducts, and 4 commercially sourced conventional media (peat moss, coco coir, biochar, and compost). For all horticulturally relevant characteristics mentioned, our results for the conventional media were similar to those of previous studies on potting media properties. *Typha* products showed similar physical characteristics to the commercial media, but chemical characteristics were different and might pose challenges. Nitrogen Drawdown Index (NDI) results showed that shredded *Typha* immobilized N, making this product less suitable for horticulture. Conductivities exceeding the suggested upper limit for growing media (3.5 dS/m) proved to be the main issue for composted *Typha* (4.6 dS/m) and *Typha* biochar (29.1 dS/M), but these defects may be corrected through rinsing and, for *Typha* biochar, a reduction in pyrolysis temperature. Ultimately, results of this study suggest that, with some refinement in processing to improve chemical characteristics, *Typha* biochar and *Typha* compost may have a valuable place in potting mixes. If so, this value-added *Typha* product would provide a financial incentive to harvest problematic stands of *Typha* and therefore their constituent nutrients from eutrophic wetlands, helping to mitigate the causes of harmful algal blooms and providing an environmentally friendly alternative to the widespread, destructive practice of mining sphagnum peat moss.

Keywords Biochar; Compost; Eutrophication; Substrates; Wetlands

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Study photograph Jerry Arguello surveys the *Typha* stand prior to harvest, 2023 February 22. (Photograph by Kyle D. Boutin.)

1. Introduction

Wetlands are an effective tool for removing the nitrogen (N) and phosphorus (P) from surface waters that fuel harmful algal blooms (Land et al. 2016). In wetlands receiving high nutrient loads, plants in the genus *Typha* tend to dominate, forming monotypic stands that are often seen as problematic by land managers (Bansal et al. 2019). These "cattail invasions" are typically managed via herbicides, which are known to promote the nutrient enrichment that contributes to *Typha* dominance (Lawrence et al. 2016). An alternative approach of *Typha* harvest has been suggested as a means of controlling *Typha* while sustainably exporting nutrients from eutrophic wetlands (Grosshans 2014; Lawrence et al. 2016; Alsadi 2019). Work by Zhou et al. (2017) in South Florida's Indian River Basin, United States, found that the aboveground, harvestable part of the cattail contained roughly 96 kg of total N and 5.6 kg of total P per hectare. Despite this clear potential for nutrient recovery, harvests rarely occur due to the low value of *Typha* biomass compared to the relatively high costs of harvest (Svedarsky et al. 2016). Here, we investigate the possibility of adding value to harvested *Typha* through the production of 3 potential substitutes for sphagnum peat moss in horticultural growing media. If operable, this strategy could provide a financial incentive for *Typha* harvest while combining the benefits of nutrient removal from the wetlands with decreasing the demand for sphagnum peat moss, a product with negative repercussions for wetlands and the global climate (Poulin et al. 1999; Mazerolle 2003; Cleary et al. 2005). Furthermore, if wetland vegetation could become a source of income, landowners might view it more favorably, leading to increased wetland conservation, restoration, and construction. This preliminary study of the potential of *Typha* as a horticultural feedstock evaluates the horticultural suitability of 3 *Typha domingensis* bioproducts (shredded *Typha*, *Typha* compost, and *Typha* biochar) through an evaluation of their physicochemical attributes. Barrett et al. (2016) cautioned against comparing data among published studies due to the wide variety of methods used in the analysis of growing media. For this reason, we included 4 commercially sourced conventional growing media in this study that would help contextualize our *Typha* results: sphagnum peat moss, coco coir, biochar, and compost. We found only one prior study to have investigated the potential of *Typha* as a growing medium (Leiber-Sauheitl et al. 2021). Our study is the first to investigate *Typha* compost or biochar for horticultural use.

Currently, sphagnum peat moss is the most widely used constituent in potting media due to its low cost, abundance, and horticulturally favorable physicochemical properties (Barrett et al. 2016; Carlile et al. 2019). From an environmental standpoint, however, the mining of peat poses 2 major issues: It necessitates the direct degradation of the peat bogs being mined which, even if restored, can take thousands of years to recover (Cleary et al. 2005); furthermore, the process of draining bogs for peat extraction triggers the release of large quantities of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from Earth's largest terrestrial store of organic carbon (Gorham 1995; Cleary et al. 2005). In recent years, coco coir, a fibrous waste

Highlight
If their high conductivities can be remedied, *Typha* compost and biochar could be suitable, environmentally beneficial substitutes for peat moss in horticulture. *Typha* products could shift the design and management of treatment wetlands toward nutrient recovery and carbon capture.

product of the coconut industry, has emerged as an increasingly popular and ostensibly environmentally friendly peat substitute (Abad et al. 2002, Carlile et al. 2015). Though available in large quantities without the need for mining, preparing coir for horticultural use can require freshwater-intensive processing to remove salts that would otherwise be detrimental to plant growth (Carlile et al. 2015; Barrett et al. 2016). The carbon footprints of both peat and coir are increased by the shipping inherent in their distant origins: Peat is typically harvested from boreal bogs far north of centers of ornamental plant production, while 90% of coir originates in South Asia and Southeast Asia (Cleary et al. 2005; Barrett et al. 2016; Carlile et al. 2019).

The relative environmental friendliness of a *Typha*-derived potting medium is moot if it is unsuitable for horticulture. A suitable growing medium must provide a stable balance of air and water to plant roots while providing a chemical environment that supports nutrient uptake (Barrett et al. 2016). The latter condition is not to be confused with fertility. Since substrate nutrition is largely controlled by growers through fertilization, the inherent nutrient content of a substrate is less important than its ability to retain added nutrients in plant-available forms (Handreck and Black 1994). This is exemplified by sphagnum peat, the low nutrient content and high cation exchange capacity of which render it a blank canvas for customized fertilization (Barrett et al. 2016).

The *Typha* products evaluated in this study were derived from *Typha domingensis* harvested in the Greater Everglades Ecosystem of Florida, United States, where an increase in aquatic nutrients has caused cattails to supplant the once-dominant sedge *Cladium jamaicense* (Miao and Sklar 1997; Bansal et al. 2019). As a result, *Typha* control is considered a high priority, and the plants are routinely sprayed with herbicides (Rodgers and Black 2012; Bansal et al. 2019). This region is also a hub of containerized plant production: In the year 2020, Florida produced 70% of the foliage plants sold in the United States and sold $1.14 billion in wholesale plants (USDA 2021). Therefore, a potting medium derived from South Florida *Typha* could offer a local, abundant, and environmentally friendly alternative to sphagnum peat moss, at the epicenter of America's ornamental plant production.

The purpose of this study was to evaluate the horticultural viability of *Typha domingensis* bioproducts as sustainable alternatives to conventional growing media, with a focus on their physicochemical properties relevant to horticulture. To achieve this, our study sought to accomplish the following objectives:

- An assessment of pH, electrical conductivity (EC), and nitrogen drawdown index (NDI) of *Typha*-based substrates alongside commercially available growing media to determine chemical suitability for plant growth.
- An evaluation of water holding capacity (WHC) and dry bulk density (DBD) of *Typha* bioproducts alongside commercially available substrates to determine physical properties and practicality in horticulture.

Through these assessments, this study investigated the potential of *Typha*-derived growing media to serve as an alternative to peat moss in horticulture. If feasible, these value-added *Typha* products would offer an economically viable and eco-friendly solution for the horticulture industry and encourage a new framework for the design and management of treatment wetlands in which nutrient recovery through biomass harvest is prioritized.

2. Materials and Methods

2.1 *Typha* Harvest

Harvest took place within a shallow ditch on the campus of Florida Gulf Coast University (FGCU) in Fort Myers, Florida, United States (26°27'51.1", -81°46'14.6"), on 2023 Feb 22. Approximately 10 m^2 of a stand of *Typha domingensis* was harvested with a machete. Harvest was timed to coincide with the onset of *Typha*'s reproductive stage in order to maximize the quantity of nutrients harvested (Grosshans et al. 2011). Immediately after harvest, plants were transported to a nearby site for processing.

2.2 Bioproduct Processing and Sourcing

The *Typha* harvest was dried on a cement pad for one week before being fed through a Harbor Freight Tools PREDATOR 6.5 horsepower chipper shredder, yielding approximately 200 L of shredded material.

2.2.1 Composted Typha *(CT)*

Half of this shredded material (approximately 100 L) was separated for composting, which was carried out by FGCU's Gulf Coast Compost organization using the Berkeley method (Raabe 1981). Partway through the composting period, 0.5 L of blood meal was mixed into the *Typha* to decrease the C:N ratio and accelerate decomposition. After 68 days of composting, the Composted *Typha* (CT) was shipped to the Wet Ecosystem Research Group lab at North Dakota State University (NDSU), Fargo, North Dakota, United States.

2.2.2 Shredded Typha *(ST)*

The remaining 100 L of shredded *Typha* was air-dried outdoors, then shipped to the Wet Ecosystem Research Group lab at NDSU. 30 L of this material was set aside as Shredded *Typha* (ST).

2.2.3 Pyrolyzed Typha *(PT)*

The remaining 70 L of dry, shredded Typha was pyrolyzed (heated in the absence of oxygen to create biochar) in batches in a 20-L steel cylinder over an outdoor fire on 2023 May 2, at a farm in Ada, Minnesota, United States. The cylinder was capped at both ends to ensure an anoxic environment, and it featured a small (approximately 1 mm) hole drilled into one of the caps to prevent the build-up of pressure. Dry firewood was piled around the loaded cylinder and then lit using a propane torch. Wood fires can reach 962 °C – 1000 °C, much higher than the 400 °C – 800 °C typical for laboratory biochar production, but in a similar temperature range as traditional and low-cost pyrolysis methods like flame-curtain kilns (Maggetti et al. 2011; Prurapark et al. 2020; Tomczyk et al. 2020; Cornelissen et al. 2023). Each fire burned until all fuel was consumed (approximately 45 mins), then the cylinder was left to cool naturally for an additional 45 mins before being opened for biochar retrieval. The retrieved biochar was designated as Pyrolyzed *Typha* (PT).

2.2.4 Typha *Blend (3T)*

Equal volumes of each *Typha* bioproduct (one-third each of CT, ST, and PT) were combined to form a *Typha* blend (3T). 3T was included in the analysis to determine if any of its components had an outsized impact on resultant properties.

2.2.5 Commercial Growing Media

The commercial products purchased for use in this analysis were Schultz® Canadian Sphagnum Peat Moss (SPM), SPONGEASE™ Coco Coir (CCR), Wakefield™ Biochar (BCH), and Old Potters™ Organic Compost (CMP). SPM was purchased from Menards® in Fargo, North Dakota, United States. CCR, BCH, and CMP were purchased through Amazon.com Inc.

2.3 Physicochemical Evaluations

pH and EC were determined following the saturation extract method (Warncke 1986). pH governs the availability of plant nutrients, while EC indicates whether the substrate contains harmful levels of salts. Three, 400 mL samples of each medium were saturated with deionized (DI) water and mixed to form 24 media slurries, which then equilibrated for 90 mins. Filtrates were then collected from each slurry using a Büchner flask. pH and EC of the filtrates were measured using a Fisherbrand™ accumet™ AB15 Basic pH meter and a Hach® SensIon™378 EC probe.

The NDI measures a substrate's propensity to immobilize soil N, rendering it unavailable to support plant growth (Handreck 1992). For each medium, six, 400-mL plastic nursery pots were filled to 300 mL and "charged" with a 75 mg/L N potassium nitrate (KNO_3) solution. Immediately after charging, a filtrate was collected from 3 pots of each medium, while the remaining pots were covered with loose-fitting plastic lids and incubated at 21 °C for 96 h. After incubation, filtrates were collected from the remaining 3 pots of each medium. Concentrations of nitrate (NO_3^-) for all collected filtrates were measured with a Hach® NITRATAX plus sc Sensor. The NDI was calculated for each material by dividing the average NO_3^- concentration from the filtrate of the 3 incubated pots by the average NO_3^- concentration of the 3 filtrates collected immediately after KNO_3 charging.

Percent WHC measures a substrate's ability to hold water following irrigation. WHC was measured using 400-mL plastic nursery pots filled with 350 mL of media. Three pots of each material were watered, then set in trays flooded with tap water for 24 h to reach complete saturation. Afterward, pots were placed on a wire rack until all drainage ceased. Pots were weighed immediately after draining, then placed in a drying oven at 60 °C for 72 h before being reweighed. WHC was calculated as a percentage by dividing the mass of water in the saturated sample by the 350 mL volume of the container and multiplying the result by 100 (Wallach 2019). WHC is largely a function of substrate particle size, with media composed of smaller particles having a greater ability to hold water (Carlile et al. 2015). With this in mind, we conducted a simple particle size distribution (PSD) to aid in explaining differences in WHC between media. Three, 100 g samples of each material were manually sifted through a 2-mm sieve for 2 mins each. The percentage of the 100 g mass of each material consisting of particles smaller than 2 mm was recorded.

DBD is the mass of dry substrate per unit volume. Materials with high DBD may be prohibitively expensive

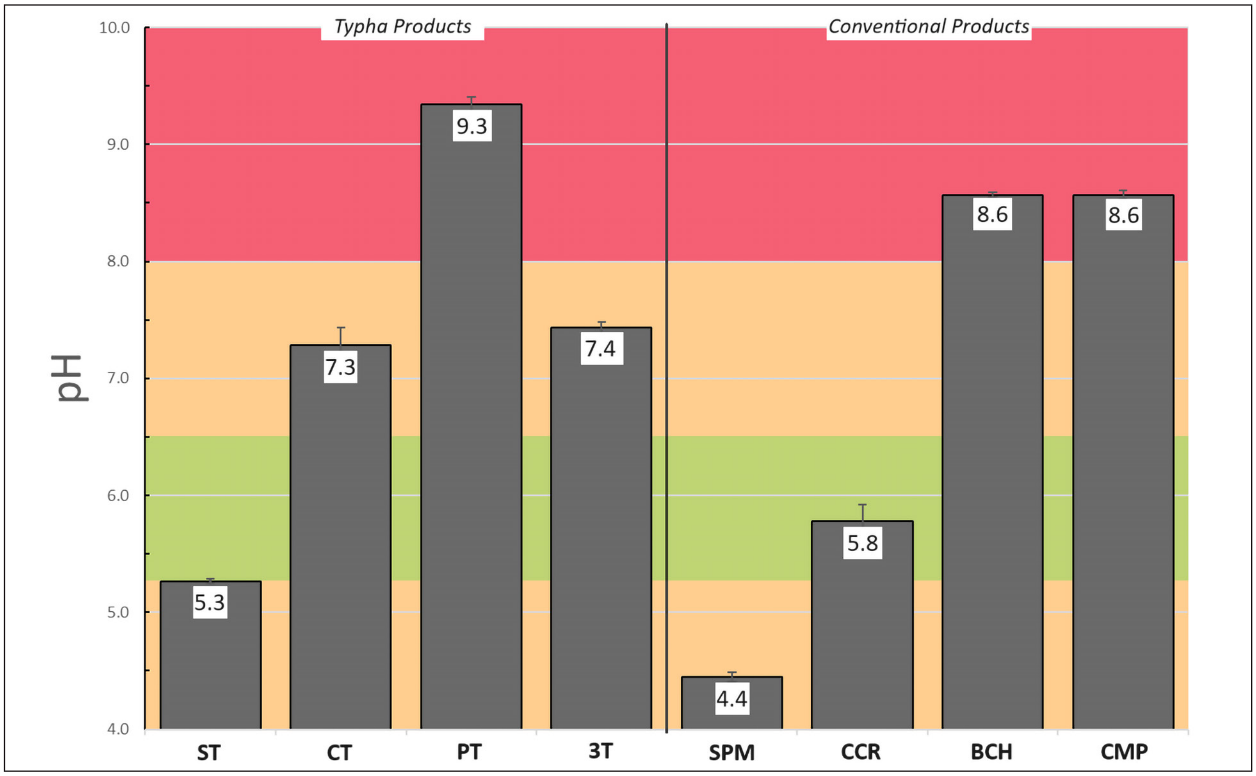

Fig. 1 Average pH ± standard deviation for each medium, n=3. The green region spanning 5.3 to 6.5 represents the optimum pH values for growing media (Abad et al. 2001), the red region at and above 8.0 represents pH values too high for most plants, and the yellow regions indicate pH values outside of the optimum but within a tolerable range for most plants (Pennisi and Thomas 2009). ST=Shredded *Typha*, CT=Composted *Typha*, PT=Pyrolyzed *Typha*, 3T=*Typha* blend, SPM=sphagnum peat moss, CCR=coco coir, BCH=commercial biochar, CMP=commercial potting compost.

to transport (Carlile et al. 2015). DBD was measured in 250-mL beakers, with 3 replications for each medium. Beakers were filled in thirds; after each third, beakers were tapped on a countertop to uniformly pack the particles and collapse any potential voids. DBD was measured by dividing the mass of dry materials by the volume of the beaker (Farhain et al. 2022).

2.4 Statistical Analysis

pH, EC, WHC, DBD, and PSD analyses measured 3 samples of each medium. For NDI, the index value for each medium is the average of the NO_3^- concentrations from the 3 filtrates taken after incubation divided by the average of the NO_3^- concentrations from the 3 filtrates taken at charging.

3. Results

3.1 pH

pH ranged from 4.4 (SPM) to 9.3 (PT) (see Fig. 1). No generalizable discrepancies were evident between pH values of *Typha* products versus conventional products. Rather, differences in pH were associated with processing: Media containing composted and/or pyrolyzed materials (CT, PT, 3T, BCH, CMP) were alkaline (pH range from 7.3 to 9.3) while raw materials (ST, SPM, CCR) were acidic (pH range from 4.4 to 5.8). The 7.4 pH of 3T approximated the average of its constituents.

3.2 Electrical Conductivity (EC)

Conductivities for the 4 conventional media ranged from 0.2 dS/M (SPM) to 2.9 dS/M (CMP) (see Fig. 2). Conductivities of the 3 *Typha* products were higher than those of the conventional products, ranging from 4.6 dS/M (CT) to 29.1 dS/M (PT). Composting decreased the EC of ST from 7.9 dS/M to 4.6 dS/M, while pyrolysis increased it to 29.1 dS/M. The 13.3 dS/M conductivity for 3T approximated the average of its constituents.

3.3 Nitrogen Drawdown Index (NDI)

NDI values ranged from 0.26 (3T) to 1.04 (CMP) (see Fig. 3). CT's 0.95 NDI was the second highest among the materials tested, but the 3 lowest NDI values came from *Typha* products. ST (NDI = 0.35) was the only material that exhibited obvious microbial growth

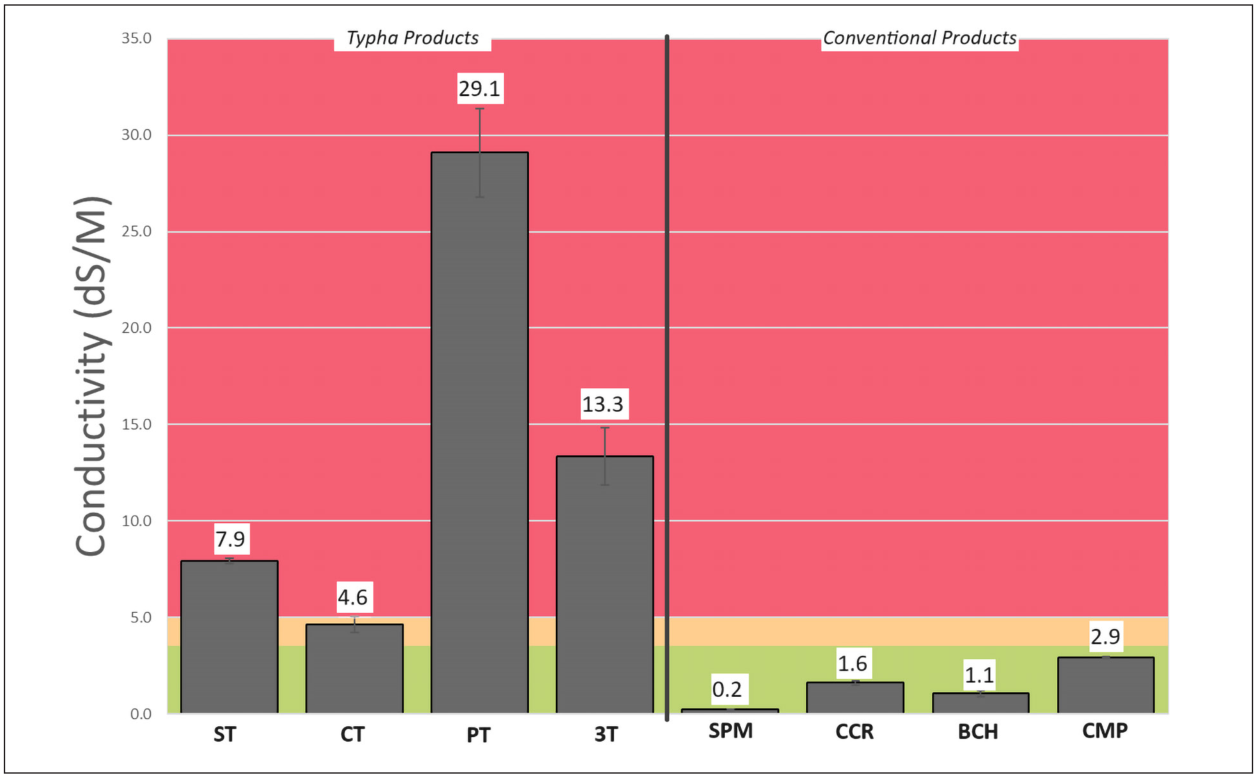

Fig. 2 Average conductivity ± standard deviation for each medium, n=3. The green, yellow, and red regions represent "Optimum," "High," and "Very High" conductivities, respectively (Warncke 1986). ST=Shredded *Typha*, CT=Composted *Typha*, PT=Pyrolyzed *Typha*, 3T=*Typha* blend, SPM=sphagnum peat moss, CCR=coco coir, BCH=commercial biochar, CMP=commercial potting compost.

following incubation, a sign of the material's propensity toward decomposition and therefore N immobilization when fertilized. 3T's 0.26 NDI fell below the 0.35 (ST) – 0.95 (CT) range of its constituents.

3.4 Water Holding Capacity (WHC) and Particle Size Distribution (PSD)

WHC ranged from 35% (ST) to 67% (BCH) (see Fig. 4). Biochars had relatively high WHC at 67% (BCH) and 56% (PT), while composts had relatively low WHC at 39% (CMP) and 37% (CT). Of the 3 non-composted, non-pyrolyzed materials, SPM (61%) and CCR (59%) showed high WHCs while the coarser ST (35%) yielded a much lower value. The 43% WHC for 3T was equal to the average of its constituents.

The percentage of each medium's mass consisting of particles smaller than 2 mm ranged from 46.9% (CT) to 95.0% (CCR) (see Supplementary Material, Fig. S1). Commercial products (range from 67.6% to 95%) all yielded higher values than the *Typha* products (range from 46.9% to 67.3%). 3T was close to the average of its constituents, with 55.6% of its mass consisting of particles smaller than 2 mm. This study found a strong positive correlation ($R^2 = 0.72$) between WHC and % mass <2 mm of media evaluated (see Supplementary Material, Fig. S2).

3.5 Dry Bulk Density (DBD)

The DBD of *Typha* products ranged from ST's 38 g/L to CT's 89 g/L (see Fig. 5). The 2 highest DBD values were those of BCH (301 g/L) and CMP (388 g/L). The 58 g/L DBD of 3T approximated the average of its constituents. Complete results from this study are compiled in Table 1.

4. Discussion

4.1 pH

Only the pH values for ST and CCR fell within the range of 5.3 – 6.5 considered to be optimal for plant growth (Abad et al. 2001). The 4.4 pH of SPM was the lowest value found in our study and corresponds with the 4.6 ± 0.3 average pH value for horticultural peats determined by Amha et al. (2010). Due to its low pH, peat is typically blended with more alkaline materials such as limestone, composts, or biochar (Carlile et al. 2015). Our 5.8 pH of CCR falls within the 4.9 – 6.0 range of coco coir pH values determined by Abad et al. (2002). Compost

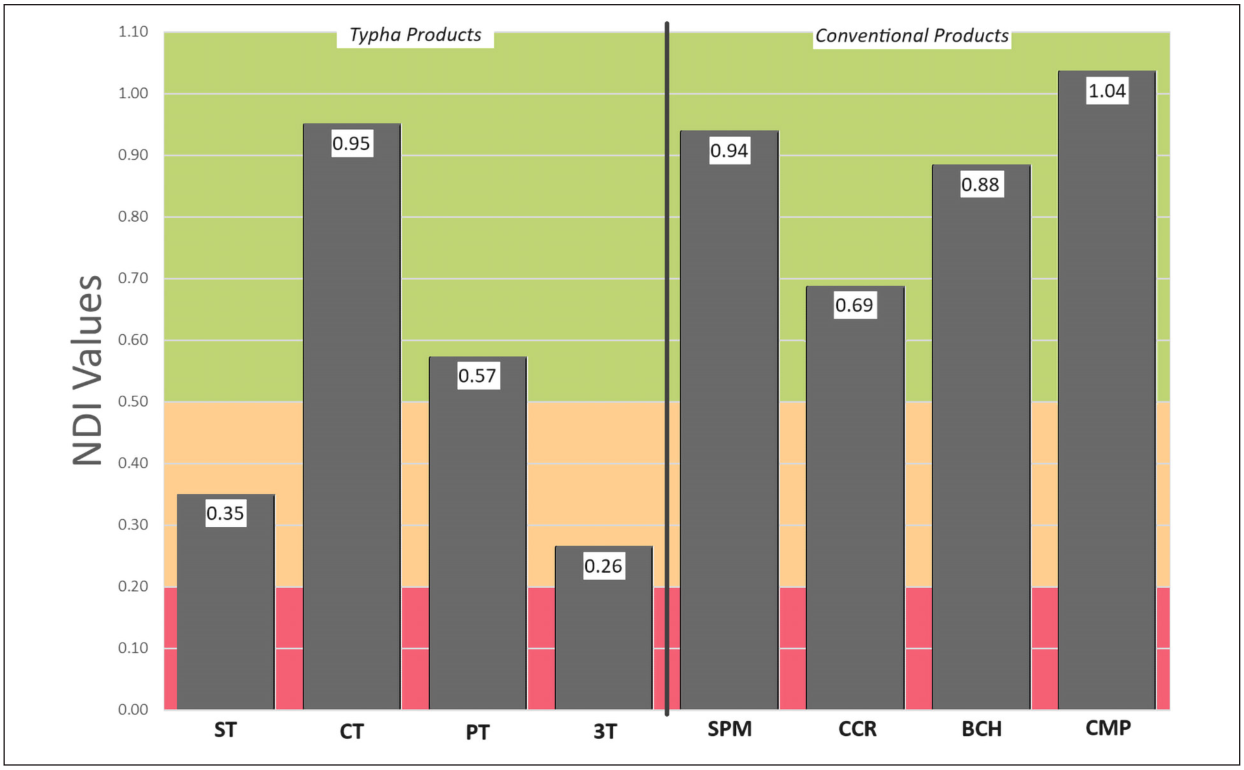

Fig. 3 Nitrogen Drawdown Index (NDI) values. The index value for each medium is the average of the nitrate (NO_3^-) concentrations from the 3 filtrates taken after incubation divided by the average of the NO_3^- concentrations from the 3 filtrates taken at charging. The green (>0.5), yellow (0.2 – 0.5), and red (<0.2) regions represent "Stable," "Semi-Stable," and "Unstable" categories of materials, respectively, as determined by NDI (Compost for Soils 2011). ST=Shredded *Typha*, CT=Composted *Typha*, PT=Pyrolyzed *Typha*, 3T=*Typha* blend, SPM=sphagnum peat moss, CCR=coco coir, BCH=commercial biochar, CMP=commercial potting compost.

and biochar exhibit a wide range of pH depending on the raw feedstocks used and, in the case of biochar, the temperature of pyrolysis (Azim et al. 2018; Tomczyk et al. 2020). High pH is a common issue that limits the use of composts as growing media (Barrett et al. 2016).

ST had a pH of 5.3, which is in accordance with the 5.4 ± 0.2 pH of *Typha angustifolia* determined by Leiber-Sauheitl et al. (2021). Composting resulted in an increase in pH to a near-neutral 7.3. For green products such as ST, composting is known to raise pH via ammonification and breakdown of organic acids (Carlile et al. 2015; Azim et al. 2018). Pyrolysis raised the pH of shredded *Typha* even further, to a considerably alkaline 9.3. Biochar pH is known to increase with pyrolysis temperature, and wood fires such as those used for our pyrolysis can reach 962 °C –1000 °C, much higher than the 400 °C – 800 °C typical for biochar production (Maggetti et al. 2011; Prurapark et al. 2020; Tomczyk et al. 2020). For this reason, we believe that the alkalinity of PT can be reduced through a reduction in pyrolysis temperature. Even at its current pH, PT could be useful as an amendment to raise the pH of acidic, peat-based mixes. Therefore, none of the *Typha* products can be deemed unsuitable due to their pH.

4.2 Electrical Conductivity (EC)

Conductivities of all conventional media tested below the 3.5 dS/m indicated by Warncke (1986) as the upper limit of optimal, while all *Typha* products exceeded this value. Our 0.2 dS/m EC measured for SPM matches the 0.21 dS/m reported by Abad et al. (2002), while our 1.6 dS/m EC for CCR falls within that study's 0.39 dS/m – 5.97 dS/m range among coco coir from various sources. As with pH, biochar EC is dependent upon feedstock material, and conductivity increases with increasing pyrolysis temperature. Literature values vary from 0.04 dS/m to 54.2 dS/m (Singh et al. 2017) and both BCH and PT fell within this wide range. The ECs of composts are highly variable depending on their source materials, but high EC values are the primary concern that limits their use in container horticulture (Carlile et al. 2015). CMP had

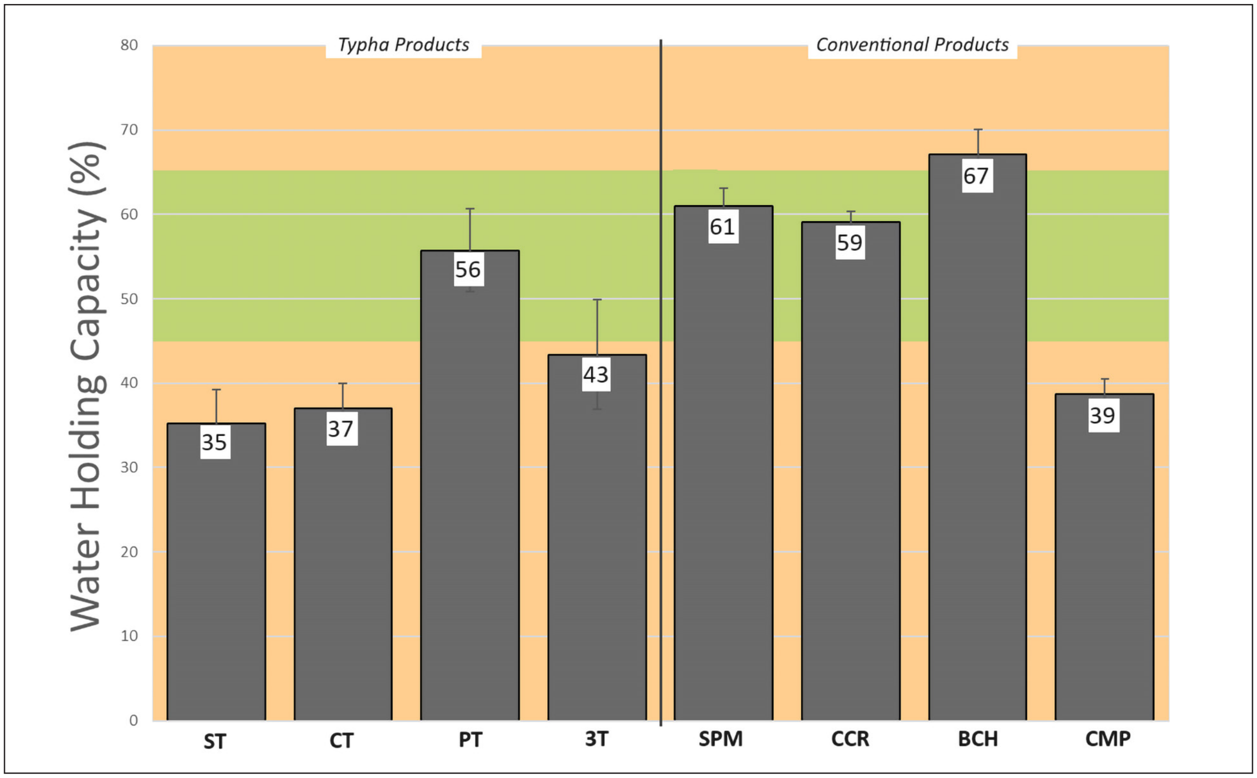

Fig. 4 Average percentage water holding capacity (WHC) ± standard deviation for each medium, n=3. The green region spanning 45% to 65% represents the optimum WHC for growing media, while the yellow regions outside this range represent suboptimal WHC (Bilderback et al. 2005). ST=Shredded *Typha*, CT=Composted *Typha*, PT=Pyrolyzed *Typha*, 3T=*Typha* blend, SPM=sphagnum peat moss, CCR=coco coir, BCH=commercial biochar, CMP=commercial potting compost.

the highest value of 2.9 dS/m EC among the commercial products we evaluated.

The 7.9 dS/m EC of raw, Shredded *Typha* (ST) examined in this study is considered too high for use in growing media (Warncke 1986). The much lower 0.55 dS/m EC reported for shredded *Typha angustifolia* in the Leiber-Sauheitl et al. (2021) study suggests that our high EC values may have been a result of species, source location, or contamination during processing. Future studies should explore these factors and investigate the specific ions causing high conductivity. The 4.6 dS/m EC of CT, while still above optimal, was the lowest of the *Typha* products. The decrease from the 7.9 dS/m EC of ST could have resulted from the leaching of salts, as it was watered and weathered periodically during the composting period. The 29.1 dS/m EC of PT is considered extremely high, and is likely to be toxic to many species of ornamental plants (Warncke 1986). As was the case with pH, this high EC likely was due in part to the high pyrolysis temperature used in this study. Higher pyrolysis temperatures increase the ash content of the resulting biochar, thus increasing salinity and conductivity (Singh et al. 2017). These results suggest that high EC is the primary barrier to *Typha* bioproduct suitability, and its causes need to be examined further. If the high EC for all *Typha* products in this study cannot be attributed to particular source conditions or corrected through refinement of processing methods, *Typha* products would not be suitable for use as primary components in growing media.

4.3 Nitrogen Immobilization

Based on the NDI stability categories in Compost for Soils (2011), none of the materials tested in this study yielded values indicating instability. All of the commercial products plus PT and CT returned NDI values above 0.5 (stable), while 2 of the *Typha* products, ST (NDI 0.35) and 3T (NDI 0.26) fell into the category of "semi-stable." Low-NDI materials can be improved by means of blending with more stable materials, processing such as composting or pyrolysis (as confirmed in this study by the higher NDI values of PT and CT), or adding N fertilizers, all of which entail increased production expenses (Barrett et al. 2016).

Our NDI of 0.94 for SPM corresponds well with the 0.95 NDI reported in Handreck (1992). The 0.69 NDI of our CCR accords with the conclusion of Cresswell (2002)

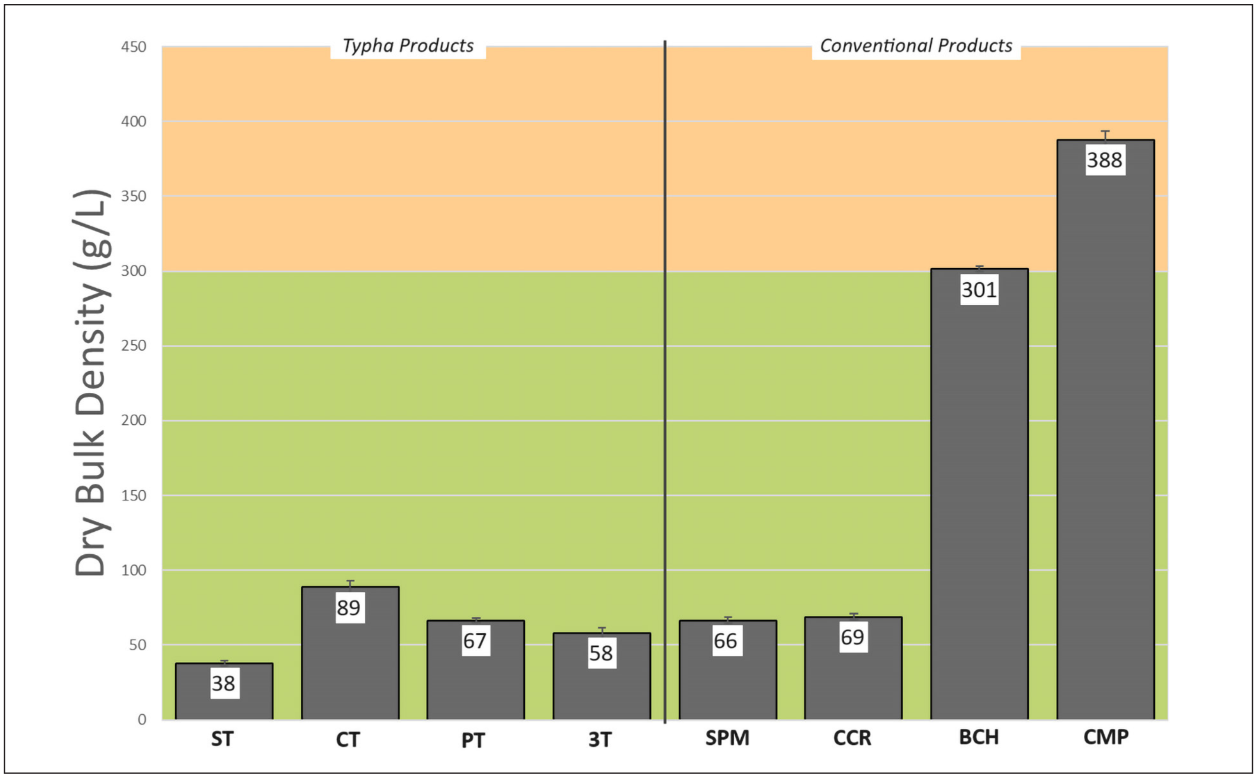

Fig. 5 Average dry bulk density (DBD) ± standard deviation for each medium, n=3. Green (<300 g/L) and yellow (>300 g/L) regions represent ideal and problematic DBD ranges. respectively (Carlile et al. 2015). ST=Shredded *Typha*, CT=Composted *Typha*, PT=Pyrolyzed *Typha*, 3T=*Typha* blend, SPM=sphagnum peat moss, CCR=coco coir, BCH=commercial biochar, CMP=commercial potting compost.

that coco coir has a higher tendency to immobilize N than peat, but that this effect is relatively minor. The slight N immobilization of BCH (NDI 0.88) could have resulted from non-biological processes, namely physicochemical adsorption of NO_3^-. In a study on the horticultural properties of biochar, Fornes et al. (2015) saw N immobilization despite low microbial respiration, leading to their conclusion that adsorption, not microbial activities, were the cause. In the case of CMP, the 1.04 NDI means that NO_3^- concentrations increased during the incubation period. This is indicative of the presence of ammonium (NH_4^+) in the compost, which underwent nitrification during incubation (Handreck 1992).

Surprisingly, this study found that blending ST (NDI 0.35) with the more stable PT (NDI 0.57) and CT (NDI 0.95) resulted in a substrate with a lower NDI (0.26) than any of the components. A possible explanation for this is that the components PT and ST reduced NO_3^- through different mechanisms: ST may have immobilized N via microbial decomposition while PT did so through adsorption (Fornes et al. 2015; Fidel et al. 2018). Though the 9.3 pH of PT reported in this study is above the levels reported by Fidel et al. (2018) at which NO_3^- adsorption occurs, the methods for determining NDI (Handreck 1992) involve the repeated flushing of substrates with DI water, a washing process known to remove soluble alkalis and therefore lower pH (Fidel et al. 2018). Furthermore, the lower pH of 3T constituents ST (pH 5.3) and CT (pH 7.3) may have created a more acidic environment favoring NO_3^- adsorption by PT.

The Leiber-Sauheitl et al. (2021) assessment of shredded *Typha* used CO_2 emissions as a measure of degradation stability and found *Typha* to be prone to decomposition, a fact that is confirmed by our relatively low NDI for ST. This propensity to immobilize N, coupled with the fact that ST was the only test substrate showing visible microbial growth following incubation with NO_3^-, suggests that future work on this topic should discard ST in favor of the more stable materials derived from its processing: PT (NDI 0.57) and CT (NDI 0.95). If the NDI of PT is indeed a result of NO_3^- adsorption, fertilizer requirements would only need to be increased initially, to satisfy the sorption sites, rather than indefinitely, as is the case regarding microbial demand. This should be investigated in future studies by “re-charging” and re-evaluating substrates after initial NDI readings, as was done in a study on sawdust-based media by Sharman and Whitehouse (1993).

4.4 Water Holding Capacity (WHC) and Particle Size Distribution (PSD)

WHC is in large part a function of PSD: With decreasing particle sizes, WHC increases while air holding capacity decreases (Carlile et al. 2015). This is supported by the strong positive correlation ($R^2 = 0.79$) between the <2 mm share of PSD and WHC found in our study. These are hardly immutable characteristics, as materials can be screened or milled to achieve a particular PSD, and thus to tailor WHC to the individual needs of growers (Carlile et al. 2015). The composting process resulted in a 23% reduction in the share of particles <2 mm between ST and CT, which we suspect was the result of washout during watering and rainfall. In the case of pyrolysis, the 10% increase in the share of particles <2 mm between ST and PT resulted from sintering and the fragmentation of long, stringy *Typha* strands that were common in ST (Downie et al. 2009).

Five of the 8 media investigated here (3 of 4 conventional, 2 of 4 *Typha*) fell within one standard deviation of the 45% – 65% normal range for WHC reported by Bilderback et al. (2005). The 2 biochars had the highest WHCs in their groups, reflecting the well-documented ability of biochars to increase WHC (Basso et al. 2013). The 35% WHC of our ST was vastly higher than the 13% reported by Leiber-Sauheitl et al. (2021). We believe that this is primarily the result of PSD: While 61.2% of the mass of our Shredded *Typha* consisted of particles <2 mm, such particles made up only 13% of theirs (Leiber-Sauheitl et al. 2021).

4.5 Dry Bulk Density (DBD)

Except for BCH and CMP, the materials ranged from 38 g/L to 69 g/L DBD, well below the 300 g/L maximum bulk density for cost-effective shipping, thus we consider all of the *Typha* products to be satisfactory in this regard (Carlile et al. 2015). Ironically, the 2 materials that exceeded 300 g/L DBD were commercial products that were shipped through the mail. Our 69 g/L DBD for CCR fell within the range of 40 g/L to 80 g/L DBD reported by Evans et al. (1996), while our 66 g/L DBD of SPM fell within the low end of the 40 g/L to 200 g/L DBD range reported by Carlile et al. (2015).

As was the case with other characteristics of biochar, its bulk density is dependent upon feedstock material and pyrolysis temperature (Downie et al. 2009). Biochar bulk densities tend to decrease with increasing temperatures due to the development of porosity; this trend reverses at pyrolysis temperatures beyond 900 °C due to sintering (Downie et al. 2009). A study by Byrne and Nagle (1997) found a linear correspondence between DBD of woody feedstocks and their resulting biochars, with biochar

Table 1 Physicochemical characteristics of growing media

	pH	Conductivity (dS/M)	Nitrogen Drawdown Index	Water Holding Capacity (%)	Dry Bulk Density (g/L)
ST	5.27 ± 0.02	7.9 ± 0.1	0.35	35.2 ± 4.0	37.9 ± 1.9
CT	7.28 ± 0.15	4.6 ± 0.4	0.95	37.0 ± 3.0	88.7 ± 4.3
PT	9.34 ± 0.06	29.1 ± 2.3	0.57	55.7 ± 4.9	66.5 ± 1.5
3T	7.43 ± 0.05	13.3 ± 1.5	0.26	43.4 ± 6.5	58.1 ± 3.4
SPM	4.45 ± 0.04	0.2 ± 0.0	0.94	61.0 ± 2.1	66.4 ± 2.0
CCR	5.78 ± 0.14	1.6 ± 0.1	0.69	59.1 ± 1.2	68.8 ± 2.0
BCH	8.57 ± 0.03	1.1 ± 0.2	0.88	67.1 ± 3.0	301.4 ± 1.9
CMP	8.57 ± 0.02	2.9 ± 0.0	1.04	38.7 ± 1.8	387.6 ± 5.8

Notes: Data presented as mean values ± 1 standard deviation. Green, yellow, and red shading indicates optimal, tolerable, and extreme values for horticultural substrates, respectively, based on ranges for each physicochemical characteristic reported in the literature. Sources for these ranges are as follows: pH (Abad et al. 2001; Pennisi and Thomas 2009); conductivity (Warncke 1986); Nitrogen Drawdown Index (Compost for Soils 2011); water holding capacity (Bilderback et al. 2005); dry bulk density (Carlile et al. 2015). ST=Shredded *Typha*, CT=Composted *Typha*, PT=Pyrolyzed *Typha*, 3T=*Typha* blend, SPM=sphagnum peat moss, CCR=coco coir, BCH=commercial biochar, CMP=commercial potting compost.

DBD typically 82% that of their feedstocks. The commercial biochar used in this study originated as woody waste of the Georgia timber industry, and its relatively high 301 g/L DBD reflects the characteristics of its feedstock (Wakefield Biochar 2024). In this study, pyrolysis increased the bulk density of *Typha* from the 38 g/L of ST to the 67 g/L of PT. We believe that this was primarily accomplished by a reduction in particle size and thus a reduction in the size of air-filled macropores.

High DBD is a common issue that limits the use of composts in growing media (Barrett et al. 2016). While this issue was evident in the commercial compost we evaluated (388 g/L), the bulk density of our *Typha* compost (88 g/L) fell comfortably within the optimal range despite increasing from the 38 g/L measured in the raw ST. Our 38 g/L DBD of ST was slightly higher than the 36 g/L DBD reported by Leiber-Sauheitl et al. (2021).

5. Conclusion

Value-added *Typha* products such as compost and biochar could provide a financial incentive to harvest problematic stands of *Typha* and thus their constituent nutrients from eutrophic wetlands, helping to mitigate the causes of harmful algal blooms and providing an environmentally friendly alternative to the widespread, destructive practice of mining sphagnum peat moss. While future work is needed to replicate this preliminary investigation of the horticultural suitability of *Typha* bioproducts using other *Typha* stands and pyrolysis conditions, our study offers some critical guidance for future work on the subject, while the close correspondence of our results for conventional media with values from the literature demonstrates the applicability of our methods.

We conclude that ST should be eliminated from consideration as a peat moss substitute due to its biological instability and propensity to immobilize N, indicated by the visible growth of mildew and the low NDI (0.35) observed in this study. Though our PT was moderately alkaline (pH 9.34 ± 0.06) and highly saline (29.1 ± 2.3 dS/M), we believe that these characteristics can be ameliorated by decreasing the pyrolysis temperature. Due to the high EC values for all *Typha* products (minimum of 4.6 dS/M), a further investigation into the causes of this, including specific ion determination and an analysis of cattails from a different source location, is needed. Despite having moderately high EC (4.6 ± 0.4 dS/M), our CT performed favorably across most metrics, but its 37.0 ± 3.0% WHC is too low to be used alone. Our results suggest that CT and PT could be blended to create a product with favorable properties, assuming their high pH and EC can be corrected. Once this improved CT-PT medium is created, the next logical step would be to directly test horticultural suitability with a seedling germination bioassay and plant growth experiments.

Though none of the *Typha* products were perfect across the physicochemical properties tested here, neither were any of the commercial products, with the exception of coco coir. It is for this reason that potting substrates are almost always a blend of various media, mixed to tailor physical and chemical characteristics to meet the needs of the plant being cultivated (Barrett et al. 2016). Results of this study suggest that with some refinement in processing to improve chemical characteristics, *Typha* biochar and *Typha* compost may have a valuable place in potting mixes. If so, *Typha* harvest can be incorporated into the design and management of treatment wetlands in a novel system, in which nutrients are recycled into value-added, environmentally beneficial horticultural products.

Supplementary Material

The online version of this article contains a link to supplementary material that includes: **Table S1:** Key to Media Tested; **Fig. S1:** Media Particle Size Distribution Graph; **Fig. S2:** Linear Regression of Water Holding Capacity and Percent Mass of Particles <2 mm; **Table S2:** Complete pH Data; **Table S3:** Complete Conductivity Data; **Table S4:** Complete Nitrogen Drawdown Index Data; **Table S5:** Complete Water Holding Capacity Data; **Table S6:** Complete Particle Size Distribution Data; **Table S7:** Complete Dry Bulk Density Data.

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Author Contributions Statement

Conceptualization: KDB; methodology: KDB; data analysis: KDB; laboratory analyses: KDB; writing original draft: KDB; review/editing original draft: MLO; investigation: KDB; resources: MLO; data curation: KDB; supervision: MLO; project administration: MLO, KDB; funding acquisition: MLO. All authors have read and agreed to the published version of the manuscript.

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The authors have no conflict of interest to report.

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The online version of this article contains a link to supplementary material that includes all supporting data.

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