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Hydraulic Behavior and Plant Performance of Redwood Bark–Coir and Palm Fiber–Peat Substrates under Deficit Drip Irrigation

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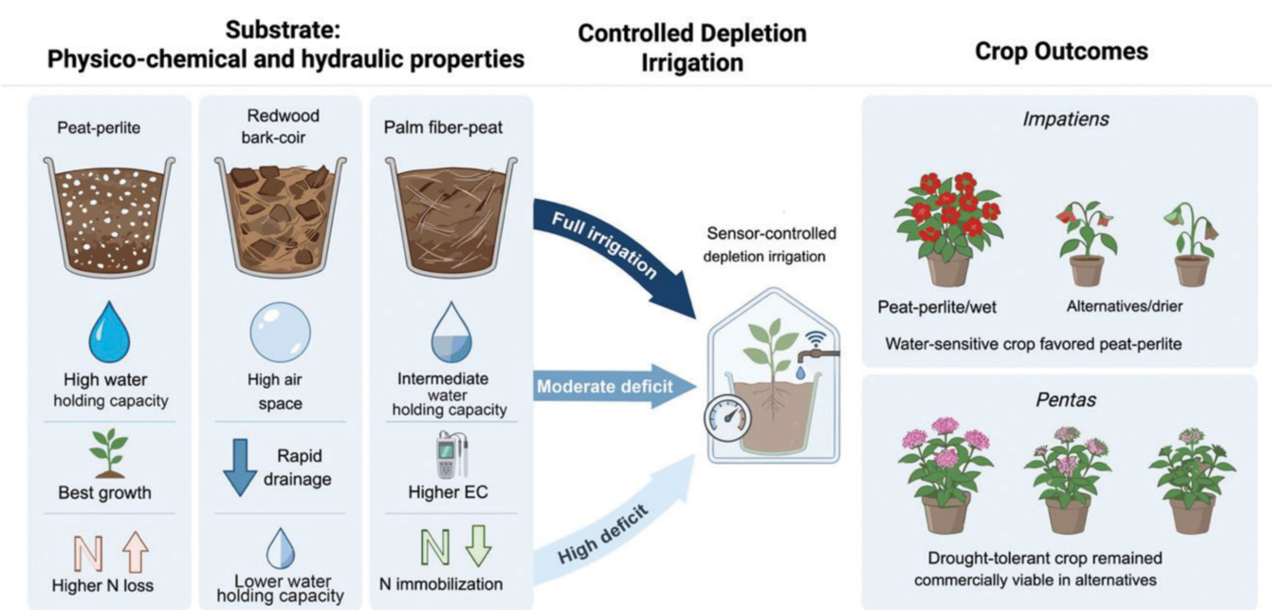
Keywords. peat alternatives, deficit irrigation, substrate, media, nitrogen draft, redwood bark, palm fiber

Abstract. Reducing reliance on peat-based substrates is a growing priority in containerized horticulture, but viable alternatives must sustain water, nutrient, and plant performance under commercial irrigation. We evaluated three substrates: a conventional peat–perlite mix, a peat-free redwood bark–coco coir blend, and a palm fiber–peat blend using recycled palm biomass. Greenhouse experiments with *Impatiens walleriana* and *Pentas lanceolata* used a 3 × 3 factorial design (three substrates × three irrigation regimes) over two 8-week production cycles. Substrate hydraulic properties, moisture dynamics, plant growth, salability, water use, and nitrogen dynamics were assessed. Substrates differed substantially in hydraulic and chemical behavior. Redwood bark–coir exhibited greater air-filled porosity and a steeper decline in water content at low matric suctions, whereas palm fiber–peat showed intermediate container capacity but elevated electrical conductivity and evidence of nitrogen immobilization. Peat–perlite produced the greatest plant biomass and salability, particularly for the water-sensitive *Impatiens*. Both alternative substrates supported commercially viable *Pentas* across irrigation treatments, indicating potential suitability for more drought-tolerant crops. Nitrogen dynamics diverged among substrates. Unaccounted nitrogen was greatest in peat–perlite, whereas palm fiber–peat retained nitrogen, suggesting immobilization. Redwood bark–coir showed limited lateral water redistribution using single-emitter drip irrigation, indicating that this irrigation method may be particularly important for substrates with low unsaturated hydraulic conductivity. Overall, partial peat substitution with palm fiber produced viable plants at a lower cost, but substrate-specific irrigation and fertility management are required to account for contrasting hydraulic and nutrient dynamics.



Introduction

Containerized plant production represents a dominant sector of modern horticulture, requiring precise control of root zone physical and hydraulic conditions to optimize crop performance. In these systems, soilless substrates play a central role in regulating water availability, aeration, and nutrient dynamics. Peat substrates are commonly used in the production of high-value products, in greenhouse floriculture, and in propagation, whereas outdoor nurseries often use by-products of the lumber industry, such as pine or fir bark. Peat-based substrates have historically served as the industry standard because of their low bulk density, favorable pore-size distribution and container capacity, high total porosity, and chemical stability (Barrett et al. 2016), and only a few disadvantages, including hydrophobicity when dry. Despite these advantages, reliance on peat-based substrates has become increasingly scrutinized. Environmental concerns associated with peat extraction, combined with rising material costs and supply limitations, have intensified efforts to reduce peat dependence and identify sustainable, alternative substrate materials (Aurdal 2025). Consequently, interest has increased in developing peat-reduced growing media incorporating low-cost, locally available, green waste or by-product–derived organic materials. Substrates used in containerized systems must maintain a balance between air-filled and water-filled pore space, particularly during irrigation and subsequent dry-down periods (Fonteno and Bilderback 1993). Because of higher porosity than mineral soils, container media water availability depends heavily on pore structure and hydraulic conductivity, which define the amount of water accessible to roots during drying (Fields et al. 2014b). Alternative organic substrates, including coconut coir and bark-derived substrates, have therefore been widely investigated as partial or complete peat replacements. More recently, locally sourced materials, such as ground palm residues and redwood bark, have emerged as promising candidates for peat substitution. In California, USA, this interest is supported further by California Senate Bill 1383 (LA Sanitation 2026), which sets a 75% reduction target for organic waste sent to landfills, incentivizing the diversion of locally generated green waste into higher value uses such as horticultural substrates. Sourcing locally may also provide sustainability advantages, in addition to economic benefits, as locally produced materials often have lower global warming potential and reduced transport costs (Brumfield et al. 2018). Previous studies (e.g., Gruda 2022) indicate that the performance of peat alternatives is strongly influenced by material variability, processing methods, and irrigation management, highlighting the need for comparative evaluations of alternative substrates under differing irrigation regimes. However, current substrate research remains unevenly distributed across material types, with certain organic alternatives receiving substantially greater attention than others.

Among the peat-alternative substrates, coconut coir and bark-based materials represent two of the most studied categories. Coconut coir is widely regarded as a successful peat alternative because of its high total porosity, strong container capacity, resistance to microbial degradation, and excellent rewettability characteristics (Barrett et al. 2016; Gruda 2019; Xiong et al. 2017), and frequently serves as a benchmark material in peat-reduction studies.

Bark-based substrates are similarly well established in the horticulture industry, although regional use varies depending on local lumber sources (Jackson and Fonteno 2015). For example, container nurseries in the eastern United States primarily use pine bark, whereas redwood woodchips or shavings and Douglas fir bark are the predominant choices in the western United States (Choi et al. 2018; Wright and Browder 2005). These substrates typically exhibit high air-filled porosity, adequate container capacity, and pathogen suppression characteristics (Kingston et al. 2017), but elevated carbon (C)-to-nitrogen (N) ratios may promote N immobilization during microbial decomposition, necessitating careful fertility management (Ceglie et al. 2015; Thiessen et al. 2023). Despite its regional prevalence, redwood bark—a by-product of coast redwood (*Sequoia sempervirens*) timber production—remains comparatively understudied relative to pine and Douglas fir bark. Given structural and compositional differences among bark species, extrapolation from pine- or fir-based studies remains uncertain, as species-dependent variation in particle morphology, decomposition resistance, and hydraulic properties may influence substrate performance substantially.

Palm tree–derived materials have recently attracted attention as potential peat alternatives, particularly in regions with abundant palm biomass residues, offering potential sustainability advantages through resource utilization and circular economy strategies. Studies indicate that palm fiber materials can substitute a portion of peat effectively; however, performance frequently declines at high substitution rates (Ceglie et al. 2015; Pooyeh et al. 2012). Reported limitations include elevated salinity and chloride accumulation: variability associated with the material source and processing techniques (Gomis et al. 2022; Mahmoud et al. 2024). Empirical evaluations of palm fiber substrates remain limited relative to coconut coir and conventional bark materials, and the physical and hydraulic performance of ground palm residues remains insufficiently characterized.

Bark-, coir-, and palm-derived substrates can serve as viable peat-reduced growing media; however, their performance is strongly influenced by irrigation management. Organic substrates differ fundamentally from mineral soils and exhibit distinct hydrological responses to repeated irrigation–drainage cycles (Caron and Michel 2015; Fonteno and Bilderback 1993). Substrate properties such as wettability, unsaturated hydraulic conductivity, and effective plant-available water govern water uptake during dry-down periods and influence irrigation demand, nutrient transport, and crop stress responses (Fields et al. 2014b, 2017). Substrates with comparable water-holding capacity can frequently differ in water capture, depending on the irrigation method, particularly under different initial volumetric water contents (Schulker et al. 2020). Coconut coir and pine bark have been shown to maintain rewettability and water capture relative to peat (Schulker et al. 2020). Despite these findings, irrigation is often treated as a secondary factor in peat substitution studies, limiting understanding of substrate–irrigation interactions. Consequently, comparative assessments integrating substrate composition with irrigation regime are needed to evaluate the feasibility of alternative materials under practical greenhouse management conditions.

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We used ChatGPT (GPT-5.5, OpenAI, San Francisco, CA, USA)to assist with development and troubleshooting of R code(version 4.5.2; R Foundation for Statistical Computing, Vienna, Austria)for figure generation. FigureLabs AI illustration tool was used in the preparation of the graphical abstract. We reviewed, edited, and take full responsibility for all manuscript content, interpretations, and conclusions.

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We evaluated three blended organic substrates with similar available water, obtained by incorporating regionally available materials—specifically, ground redwood bark mixed with coconut coir and ground palm fiber mixed with peat, relative to a conventional peat–perlite substrate. The objectives were 1) to quantify differences in substrate physical and hydraulic properties, 2) to assess substrate moisture dynamics under controlled-deficit irrigation regimes, and 3) to evaluate implications for plant growth, water use, irrigation efficiency, and N dynamics. We hypothesized that incorporation of alternative organic components would modify substrate pore structure and hydraulic behavior, thereby influencing container capacity, rehydration responses, and plant resource use efficiency.

Materials and methods

Two experiments were conducted at the University of California South Coast Research and Extension Center in Irvine, CA, USA (lat. 33.690016, long. −117.718956), to evaluate the performance of three substrates across three irrigation regimes for two ornamental crops in a 3 × 3 factorial design. The first experiment was conducted from 22 Apr to 13 Jun 2025, growing *Impatiens walleriana* Hook. f.; the second, from 20 Jun to 8 Aug 2025, growing *Pentas lanceolata* (Forssk.) Deflers.

Substrate formulation and physicochemical properties. Three substrates were evaluated: 1) a commercial peat–perlite mix (peat–perlite) (Sunshine Mix #4; Sun Gro Horticulture Canada Ltd, Agawam, MA, USA), 2) a redwood bark–coco coir mix (redwood bark mix) consisting of 70% redwood bark and 30% coco coir by volume, and 3) a palm fiber–peat mix (palm fiber mix) consisting of 50% ground palm-derived green waste and 50% peat–perlite.

The redwood bark mix was provided by ASG Developments Inc (Wildomar, CA, USA) and consisted of redwood bark ground three times in a hammer mill (referred to as triple grind in the industry) from northern California blended with finely ground coco coir (pith and fiber) from Guerrero, Mexico, supplied by AgroCoco (Menifee, CA, USA). The redwood bark was rehydrated and amended with calcium nitrate (2.12 $kg \cdot m^{-3}$; equivalent to 0.33 $kg \cdot m^{-3}$ N) 3 weeks before blending it with coco coir. This practice is used to offset potential N immobilization commonly observed in wood-based substrates.

The palm fiber material was obtained from a commercial green collection facility (San Pasqual Valley Soils, Escondido, CA, USA) and derived from processed urban palm tree residues. Palm fiber was blended with the peat–perlite substrate using a 141-L concrete mixer for 3 min to ensure homogeneity. The mixture was subsequently rehydrated according to standard nursery practices for substrate preparation.

Before potting, substrates were loosened and hydrated before an equal mass of each substrate (603 g redwood bark mix, 578 g palm fiber mix, and 518 g peat–perlite) was transferred to trade 1-gal high-density polyethylene containers (depth, 16.51 cm; height, 17.78 cm; fill volume, 1920 mL) and tapped gently three times to achieve the target packing density.

Substrate physical properties were characterized by an independent laboratory (Waypoint Analytical, Anaheim, CA, USA) using the 15.2-cm (6-inch) tall porometer method, a modification of the standard North Carolina State University porometer technique (Fonteno et al. 1995), at five moisture states: container capacity; 5, 10, and 50 kPa matric potential; and oven-dry conditions. Reported properties included bulk density, total porosity, air-filled porosity, container capacity (in the literature also referred to as water-holding capacity), and plant-available water.

Particle density was calculated from the measured porosity and dry bulk density with the following formula:

$$\text{Particle density} = \frac{\text{Bulk density}}{(1 - \text{Porosity})}.$$

In addition, substrate pH (saturated media extract method) and electrical conductivity (ECe; saturated media extract method) were measured in-house using a portable EC and pH meter (Bluelab Combo Meter; BlueLab Corp Ltd, Tauranga, New Zealand).

Experimental design. A completely randomized design consisting of three substrates and three irrigation regimes was implemented in both greenhouse experiments. The factorial combination of substrates and irrigation treatments produced nine treatment combinations. Eight replicate containers were assigned to each treatment, resulting in 72 containers per experiment. Three irrigation regimes (full, moderate-deficit, and high-deficit irrigation) were established to maintain progressively drier moisture conditions. Daily irrigation volumes applied under each irrigation regime for the two greenhouse experiments are reported in Supplemental Table 1. The full-irrigation treatment roughly followed the measured evaporation in the greenhouse, whereas the moderate-deficit and high-deficit treatments were approximately two thirds and one third of the observed evaporation, respectively (Supplemental Fig. 1). Irrigation was applied at night, and water was delivered gradually in 30-s increments (∼11 mL per increment) every 2.5 min to allow the substrates to absorb the applied water. The irrigation schedule for each treatment is reported in Supplemental Table 1.

Irrigation was applied simultaneously to 24 plants assigned to the same irrigation treatment via three shared irrigation lines. Consequently, irrigation treatments represent shared treatment effects within irrigation groups rather than strictly independent container-level irrigation events. Plants within an irrigation treatment received identical watering events. Irrigation was applied automatically at 0100 HR using drip emitters (Netafim WPCJ 0.32 GPH; Netafim USA, Fresno, CA, USA). Nine representative containers (one per treatment) were placed on load-cell lysimeters (LSP-10 Low Single Point Load Cell Force Sensor; Transducer Techniques, Temecula, CA, USA), and container weight was recorded at 5-min intervals using a 16-channel relay multiplexer (AM16/32B; Campbell Scientific, Logan, UT, USA) connected to a data logger (CR1000X; Campbell Scientific).

Load-cell measurements (Fig. 1) were used to quantify daily water use and substrate rehydration. Daily water use volume was calculated as the difference between the container weight measured in the morning (0500 HR, postirrigation drainage equilibrium) and at night (2300 HR) of any given day. Rehydration volume was calculated as the difference between container weight

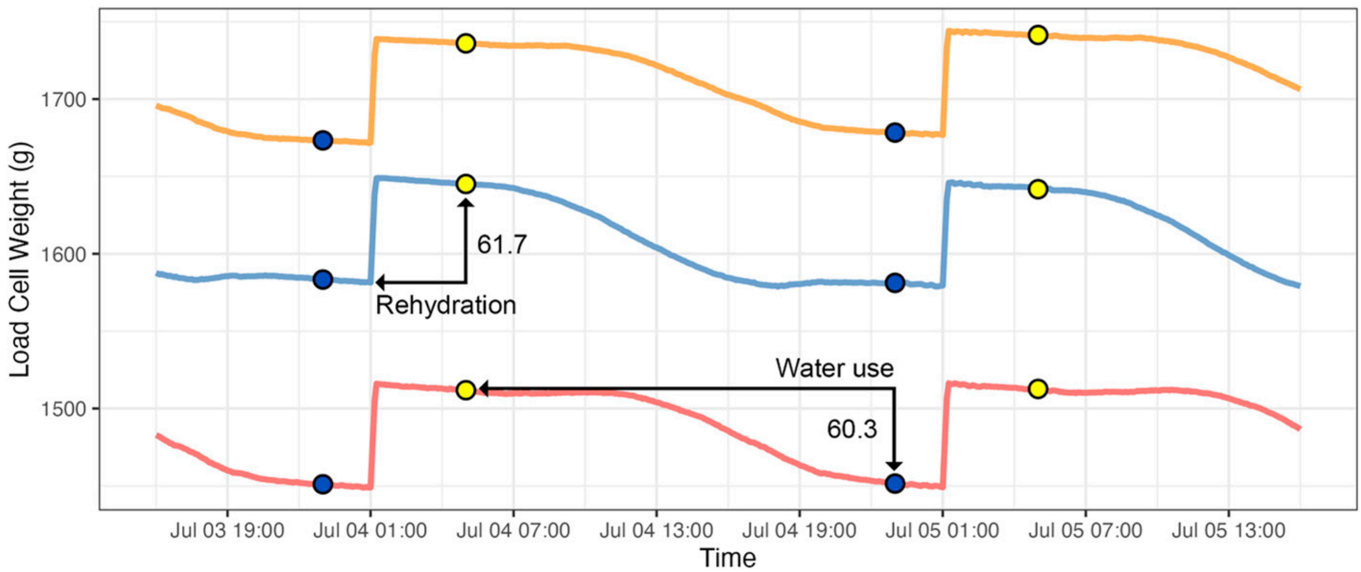

Fig. 1. Example of continuous load-cell measurements used to calculate daily water use and substrate rehydration for the three substrates [peat–perlite (blue), redwood bark mix (red), and palm fiber mix (yellow)]. Daily water use was calculated as the difference between the container weight measured at 0500 HR (postirrigation drainage equilibrium) and 2300 HR on the same day. Rehydration was calculated as the difference between container weight measured at 0500 HR and at 2300 HR the previous night, before irrigation. Marked points indicate the specific observation times used in these calculations.

measured in the morning (0500 HR) and container weight measured the previous night (2300 HR), before irrigation (Fig. 1). The rehydration fraction was defined as the rehydration volume divided by the applied water volume. Leaching was calculated as the difference between the applied irrigation volume and the rehydration volume. Volumetric water content (VWC) was calculated from the load-cell weight records as follows:

$$VWC = \frac{W_{total} - (W_{container} + W_{plug} + W_{tensiometer} + W_{stake} + W_{fertilizer} + W_{dry\ substrate})}{V_c},$$

where W_{total} is the total weight recorded by the load cell in grams, $W_{container}$ is the weight of the empty plastic container (22 g), W_{plug} is the plug weight at transplant (15 g), $W_{tensiometer}$ is the tensiometer assembly weight (354 g), W_{stake} is the irrigation stake weight (4 g), $W_{fertilizer}$ is the weight of the applied fertilizer (16 g), and $W_{dry\ substrate}$ is the dry substrate weight estimated from the dry bulk density; V_c is the container fill volume (1920 mL).

All weight differences were assumed to represent changes in water mass and were converted to water volume using a density of 1 g·mL^{-1}.

Plant culture and environmental conditions. Plant seedlings of the two ornamental species (*I. walleriana* and *P. lanceolata*) were obtained from a commercial greenhouse (Plug Connection, Vista, CA, USA). *Impatiens* (Xtreme™ Mix; Syngenta Flowers, Gilroy, CA, USA) were seeded 5 Mar 2025 and transplanted into trade 1-gal containers 23 Apr 2025. *Pentas* (Lucky Star® Mixture; PanAmerican Seed, Chicago, IL, USA) were seeded 18 Apr 2025 and transplanted 20 Jun 2025. Each container was top-dressed with 16 g controlled-release fertilizer (Osmocote Plus 15-9-12; ICL Growing Solutions, Tel Aviv, Israel). Each container was irrigated manually four times on the day of transplanting, twice immediately after plant plugs were transplanted and twice more after fertilizer application, to bring the substrates to container capacity.

Both experiments were conducted in a controlled glass greenhouse environment equipped with ridge vent passive ventilation, evaporative cooling (via swamp cooler), and a 50% Aluminet® shadecloth (Polysack, Nir Yitzhak, Israel). Air temperature and relative humidity were measured using a temperature and relative humidity probe (CS215 sensor; Campbell Scientific). Photosynthetically active radiation (PAR) was measured using a PAR quantum sensor (CS310; Campbell Scientific). The daily light integral was calculated as the cumulative daily sum of instantaneous PAR measurements. Environmental variables were recorded using a data logger (CR1000X; Campbell Scientific), which recorded at 1-min intervals.

Evaporation within the greenhouse was measured using an atmometer (ETgage, model E; ETgage Co, Loveland, CO, USA) equipped with a #30 cover, which simulates a grass reference surface. The instrument estimates atmospheric evaporative demand from water loss through a porous evaporative surface and reports evaporation as an equivalent water depth (measured in millimeters mm per day) (Supplemental Fig. 2).

At the conclusion of each experiment, plants were evaluated for marketability (salability) using visual quality ratings based on overall plant appearance, canopy fullness, and commercial acceptability (Supplemental Table 2). Shoots were harvested, and fresh biomass was recorded immediately after harvest. Dry biomass was determined after oven-drying at 100 °C for a week until constant mass was achieved.

Composite shoot samples for each treatment were submitted to an independent laboratory (Waypoint Analytical) for the determination of total N content by combustion analysis in both *Impatiens* and *Pentas*. In the *Pentas* experiment, residual fertilizer after the experiment and N content in the substrates before and after the experiment were measured. Residual fertilizer was measured by collecting and weighing slow-release fertilizer prills manually from five randomly selected containers per treatment to estimate average N recovery and N balance for each. To determine substrate N content before and after the experiment, three containers per substrate were selected randomly (one from each irrigation treatment). The substrate from these containers was combined and homogenized in a sealed plastic bag and submitted to an independent laboratory (Waypoint Analytical) for analysis.

Statistical analysis. Shoot biomass and salability ratings data were analyzed using analysis of variance within a linear mixed-effects framework implemented in R (R Foundation for Statistical Computing, Vienna, Austria). These response variables were measured on all eight replicate containers per treatment combination (72 containers per experiment). Mean separations were performed using Tukey's honestly significant difference test in the agricolae package (version 1.3-7; de Mendiburu 2023). Substrate and irrigation treatments were treated as fixed effects; replicate was treated as a random effect.

The linear regression analysis of dry weight and daily water use was performed by aggregating values from all the plants in a substrate–irrigation treatment combination for dry weight and using the water use obtained from plants monitored by load cells.

Substrate moisture dynamics, including VWC, rehydration, leaching, and daily water use, were derived from continuous load cells collected from a single, representative, instrumented container per treatment combination (nine containers per experiment). Because these data lack container-level replication, they are not subject to formal statistical inference and are interpreted qualitatively to characterize differences in hydraulic behavior among substrates across irrigation levels.

Results

Physicochemical and hydraulic properties of the substrates. Physical properties differed among the three substrates, reflecting variations in bulk density and pore structure (Table 1; Fig. 2A–C). Bulk density was lowest for peat–perlite (0.13 $g\cdot cm^{-3}$) and greater for the redwood bark mix (0.16 $g\cdot cm^{-3}$) and the palm fiber mix (0.22 $g\cdot cm^{-3}$), with a 69% difference between peat–perlite and the palm fiber mix (Table 1). Differences in bulk density reflect variation in pore structure and contribute to differences in hydraulic behavior (Fields et al. 2017).

The redwood bark mix had the greatest total porosity among the three substrates, yet at container capacity it retained the least water, with the greatest air-filled porosity (39.5%) and the lowest volumetric water content (48.2%) compared with peat–perlite (air space, 14.5%; water at container capacity, 60.7%) and the palm fiber mix (air space, 15.5%; water at container capacity, 55.4%) (Fig. 2A–C). At greater matric suction, the VWC declined in all substrates. However, the redwood bark mix showed more desaturation at 50 kPa, retaining only 22.9% of water compared with 35.9% for peat–perlite and 33.0% for the palm fiber mix. Water retention curves (Fig. 2D) reflect these differences in drainage behavior. The redwood bark mix showed earlier air entry and a steeper decline in water content, consistent with its higher fitted van Genuchten α and n parameters ($\alpha = 4.88 \cdot kPa^{-1}$, $n = 1.52$) relative to peat–perlite ($\alpha = 3.26$, $n = 1.18$) and the palm fiber mix ($\alpha = 3.47$, $n = 1.26$) (Table 1).

Readily available water (RAW), defined as the VWC between container capacity and 50 kPa, was comparable between the redwood bark mix (25.4%) and peat–perlite (24.8%), whereas the palm fiber mix provided slightly less (22.4%). In contrast, peat–perlite exhibited the greatest potentially available water (the volumetric water content calculated as the RAW plus one half of the VWC retained at 50 kPa) with a value of 42.7%, followed by the palm fiber mix (38.9%) and the redwood bark mix (36.8%).

Chemical properties also differed among substrates. The redwood bark mix exhibited the lowest pH (4.6), whereas the palm fiber mix and peat–perlite had higher pH values (6.2). The ECe was greatest in the palm fiber mix (2.2 $dS\cdot m^{-1}$), lower in peat–perlite (1.5 $dS\cdot m^{-1}$), and lowest in the redwood bark mix (0.9 $dS\cdot m^{-1}$) (Table 1). The initial substrate total N was greatest in peat–perlite (0.93%), intermediate in the palm fiber mix (0.62%), and lowest in the redwood bark mix (0.36%). Collectively, the substrates differed substantially in hydraulic behavior and intrinsic N content, establishing contrasting physical and nutritional environments for horticultural use.

Irrigation delivery and substrate moisture dynamics. Irrigation prescriptions produced distinct and sustained separation in substrate

Table 1. Hydraulic model parameters, bulk density, and initial nitrogen (N) status of the experimental substrates.

Substrate	RAW (%)[i]	PAW (%)[ii]	Bulk density ($g\cdot cm^{-3}$)[iii]	Particle density ($g\cdot cm^{-3}$)	θ_s[iv]	α (kPa^{-1})[iv]	n[iv]	Initial substrate total N (%)[v]	pH	ECe ($dS\cdot m^{-1}$)
Redwood bark mix	25.4	36.8	0.16	1.31	0.878	4.88	1.52	0.36	4.6	0.9
Peat–perlite	24.8	42.7	0.13	0.52	0.751	3.26	1.18	0.93	6.2	1.5
Palm fiber mix	22.4	38.9	0.22	0.76	0.709	3.47	1.26	0.62	6.2	2.2

ECe = electrical conductivity (saturated extract media method).

[i] Readily available water (RAW) was calculated as the difference between the volumetric water content at container capacity and 50 kPa of matric suction.

[ii] Potentially available water (PAW) was calculated as RAW plus one half of the volumetric water content retained at 50 kPa.

[iii] Bulk density was measured using oven-dry conditions.

[iv] Parameters θ_s, α, and n were obtained by fitting the van Genuchten model to laboratory soil water retention data.

[v] Initial substrate total N represents the N concentration measured at the beginning of the experiment on a dry-weight basis.

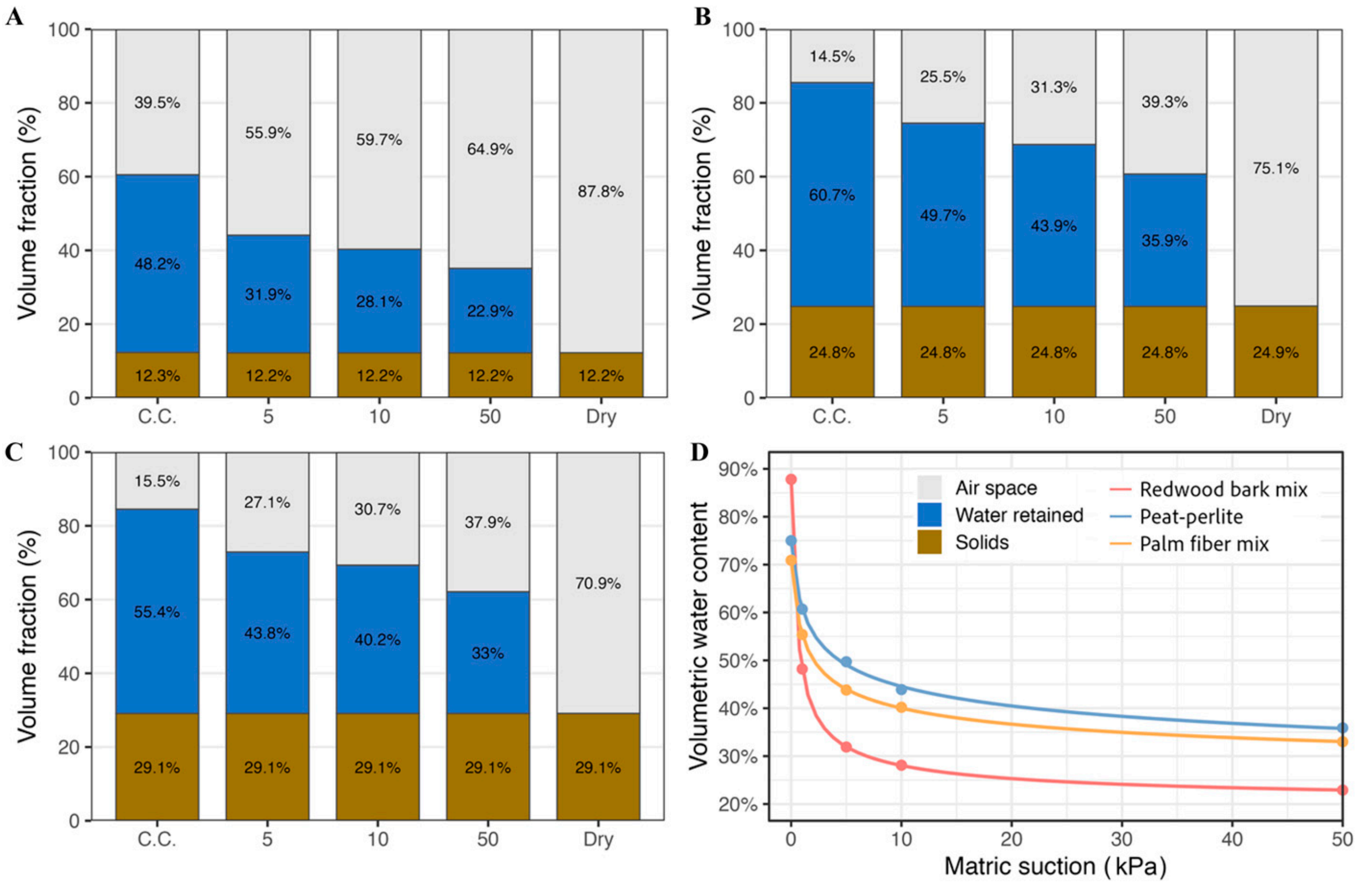

Fig. 2. Physical and hydraulic characteristics of the evaluated substrates. Panels show substrate phase composition expressed as volume fractions of solids, water retained, and air space at container capacity (CC), increasing matric suction levels (5, 10, and 50 kPa), and the oven-dry condition for redwood bark mix (A), peat–perlite (B), and palm fiber mix (C). (D) Corresponding substrate water retention curves, illustrating volumetric water content as a function of matric suction.

water status among irrigation treatments for both species (Fig. 3), although the degree of separation varied by substrates and species. The VWC (Fig. 3A and B) reflected the daily drying–rewetting cycle imposed by each irrigation treatment, declining between irrigation events and recovering sharply after each water application. Full-irrigation treatments generally maintained a greater VWC than moderate-deficit and high-deficit treatments, although separation among irrigation treatments was more pronounced in *Impatiens* than in *Pentas.* The magnitude of interevent VWC variation differed among substrates and irrigation treatments. Under full irrigation, the VWC remained consistently greatest across substrates throughout both experiments, rarely dropping to less than 0.35 $cm^3 \cdot cm^{-3}$. Peat–perlite and the palm fiber mix showed relatively similar VWC patterns, consistent with their similar water-holding capacities and water retention curve parameters (n = 1.18 and 1.26, respectively; Fig. 2D). In contrast, the redwood bark mix generally maintained a lower VWC within the same irrigation treatment, consistent with its lower container capacity and steeper retention curves (n = 1.52), which released a greater proportion of plant-available water over a more narrow matric potential range near the air-entry value.

In the *Impatiens* experiment, the VWC declined more sharply under the high-deficit treatment, coinciding with a prolonged period of extreme heat from mid-May onward (daily maximum repeatedly exceeding 38 °C) (Supplemental Fig. 2), which drove mortality across all treatments, most severely under moderate- and high-deficit irrigation. Despite constant irrigation input, water use and rehydration decreased slightly under deficit treatments during this period, possibly indicating developing substrate hydrophobicity. A brief, separate dip in water use and rehydration around 3–4 Jun coincided with a 45% decrease in the daily light integral under cloudy conditions (Supplemental Fig. 2D and E) and recovered when light levels returned to baseline. This pattern was clearest in the full-irrigation treatments of peat–perlite and the palm fiber mix, for which plants remained alive and actively transpiring, whereas plants under moderate-deficit and high-deficit irrigation had largely wilted or died by that stage.

In *Pentas*, all three irrigation treatments remained viable throughout the growing season, and rehydration and water use increased steadily as plants grew, as greater irrigation volumes were applied. The partitioning of applied irrigation into rehydration and drainage revealed clear differences among substrates and irrigation treatments. Across substrates, the high-deficit treatment produced the lowest water use and rehydration volumes, whereas the full-irrigation treatment resulted in the greatest. Under full irrigation, peat–perlite showed the greatest rehydration volumes and correspondingly lower

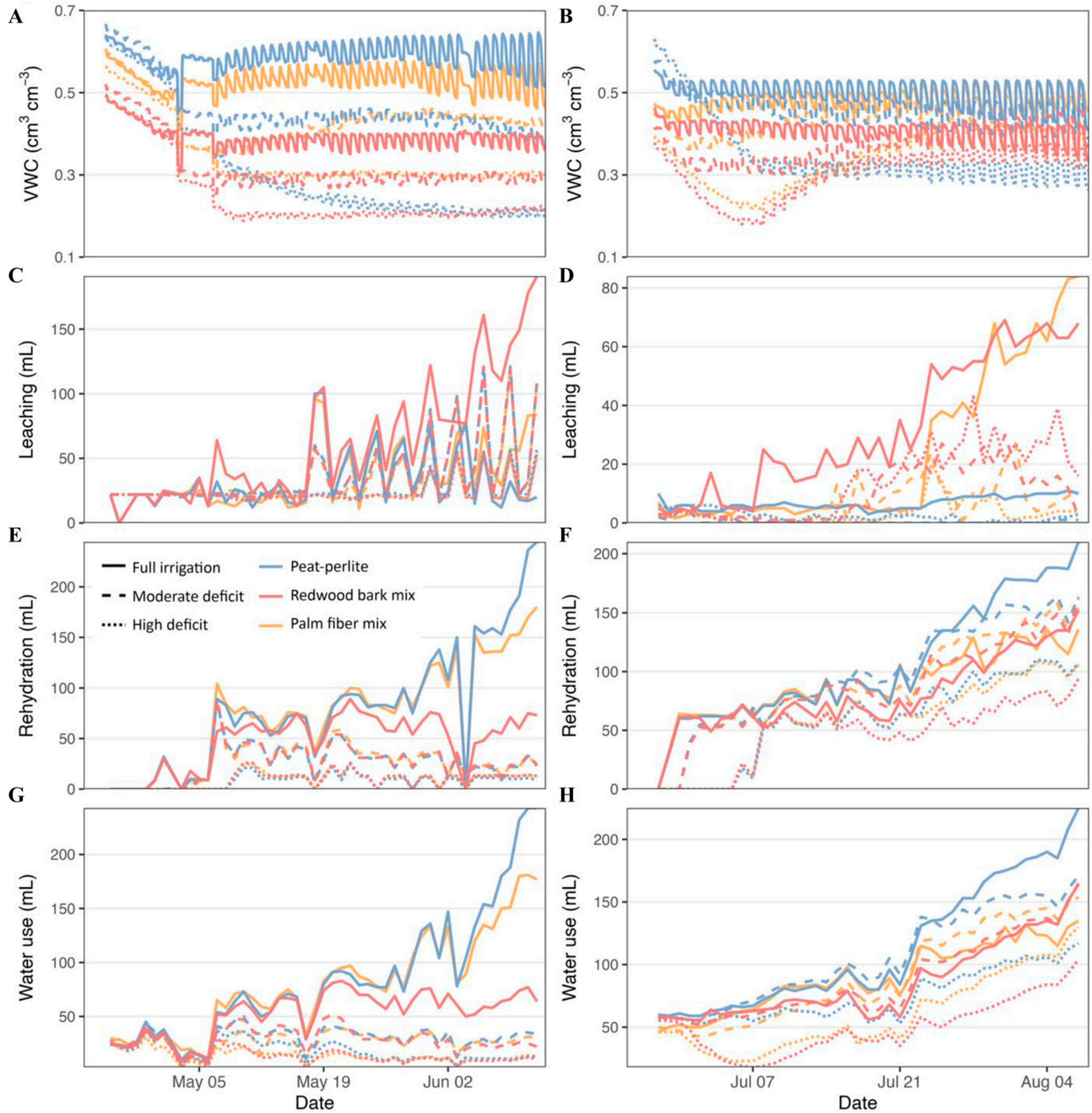

Fig. 3. Temporal dynamics of volumetric water content (VWC), leaching, rehydration, and plant water use for *Impatiens* (left) and *Pentas* (right) grown in three substrates under three irrigation treatments. (A, B) Mean substrate VWC. (C, D) Daily leaching volume per container. (E, F) Daily rehydration volumes per container postirrigation. (G, H) Daily plant water use per container. Line styles represent irrigation treatments (full irrigation, moderate deficit, high-deficit) and colors represent substrate type (peat–perlite, redwood bark mix, palm fiber mix).

leaching volumes, whereas the redwood bark mix showed the lowest rehydration volumes across all treatment combinations, with full-irrigation and moderate-deficit treatments producing similar responses.

In *Impatiens*, the rehydration fraction (Supplemental Fig. 3) declined consistently with increasing irrigation deficit across all three substrates (with a mean of 0.63 under full irrigation to 0.36 under high-deficit), likely reflecting developing substrate hydrophobicity: as preirrigation moisture drops, unsaturated hydraulic conductivity declines and applied water moves preferentially as drainage rather than redistributing through the substrate. The redwood bark mix showed the weakest irrigation treatment response. Rehydration fractions were substantially greater in *Pentas* than in *Impatiens* overall (mean, 0.90 vs. 0.49) and, in contrast to *Impatiens*, increased slightly under deficit irrigation, suggesting that hydrophobic conditions did not develop in the *Pentas* experiment.

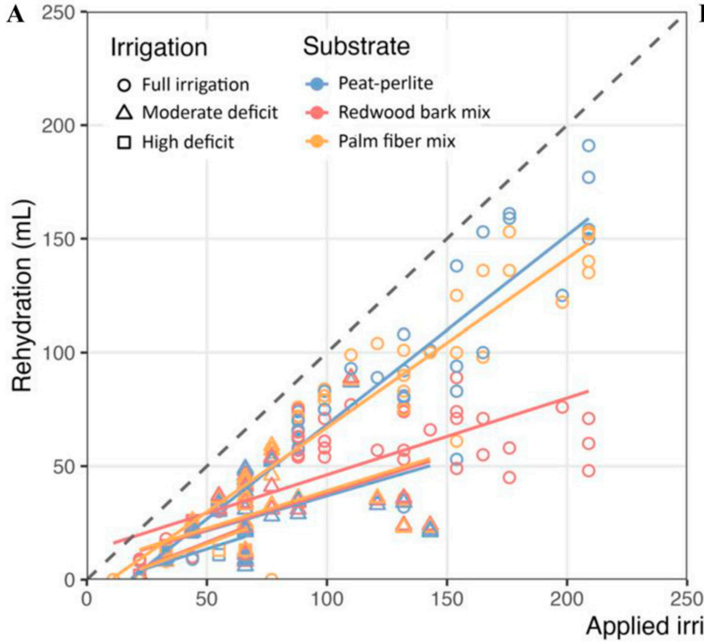

Fig. 4. Relationship between applied irrigation volume and daily rehydration response. Colors represent the three different substrates (peat–perlite, redwood bark mix, and palm fiber mix), and the symbols represent full irrigation, and moderate-deficit, and high-deficit irrigation. (A) The relationship between the applied irrigation volume and the daily mean rehydration for *Impatiens* (A) and *Pentas* (B). Points represent individual irrigation event observations derived from load-cell and irrigation schedule records; lines are fitted linear regressions by treatment.

Daily rehydration volumes were associated positively with applied irrigation in both experiments (Fig. 4), with the redwood bark mix showing a consistent lower rehydration relative to applied irrigation than peat–perlite and the palm fiber mix. Collectively, these results indicate that substrate physical properties, rather than differences in applied irrigation volume, controlled VWC and rehydration under both deficit and full irrigation. Peat–perlite maintained the most stable moisture environment, the redwood bark mix exhibited the greatest leaching, and the palm fiber mix was intermediate. In the *Impatiens* experiment, plant mortality under high-deficit irrigation coincided with the VWC dropping to less than 0.30 $cm^3 \cdot cm^{-3}$ in peat–perlite and the redwood bark mix high-deficit treatments (Fig. 3A), a threshold not crossed in any other treatment combination.

Plant growth and salability. Plant growth responses including shoot dry weight, shoot fresh weight, and salability rating differed among substrates and irrigation treatments and were strongly species dependent (Fig. 5). Dry weight represented a smaller, more variable fraction of fresh weight in *Impatiens* (mean, 7.1%; range, 3.4%–18.5%) than in *Pentas* (mean, 14.4%; range, 14.0%–14.8%), and salability ratings spanned a wider range in *Impatiens* (mean, 2.3; range, 1–4.8) than in *Pentas* (mean, 3.43; range, 2.8–4.1).

In *Impatiens*, plant loss under the moderate-deficit and high-deficit irrigation treatments reduced biomass production substantially across substrates. Of the eight plants per substrate × irrigation treatment combination, two plants survived for peat–perlite at a high-deficit, three for the redwood bark mix at a high-deficit, none for the palm fiber mix at a high-deficit; five for peat–perlite at a moderate-deficit, six for the redwood bark mix at a moderate-deficit, five for the palm fiber mix at a moderate-deficit, eight for peat–perlite at full irrigation, eight for the redwood bark mix at full irrigation, and seven for the palm fiber mix at full irrigation. Only the full-irrigation treatment produced marketable plants consistently: peat–perlite achieved the greatest growth (fresh weight, 98 g; dry weight, 5.4 g; salability rating, 4.8) followed by the palm fiber mix (fresh weight, 49.7 g; dry weight, 2.6 g; salability rating, 3.9) and the redwood bark mix (fresh weight, 37.5 g; dry weight, 1.8 g; salability rating, 3.4). Under moderate- and high-deficit irrigation, biomass and salability collapsed across all three substrates, with limited replication further constrained by plant mortality (Fig. 5).

Pentas remained commercially viable across all irrigation treatments and substrates, producing greater overall biomass and generally better quality than *Impatiens*. Peat–perlite produced the highest dry and fresh shoot weights across irrigation levels (salability rating, 3.75–4.1), whereas the palm fiber mix and the redwood bark mix produced somewhat lower but comparable biomass to each other (salability, 2.8–3.4), with substantially smaller differences among substrates than observed in *Impatiens* (Fig. 5). Unlike *Impatiens*, biomass and salability in *Pentas* were not consistently reduced under deficit irrigation relative to full irrigation.

Across both species, average daily water use was associated positively with mean dry shoot weight (Fig. 6), with a steeper relationship in *Pentas* than in *Impatiens*, reflecting greater biomass production per unit of water use. Within *Impatiens*, biomass and water use both declined with increasing irrigation deficit and with deficit-related plant mortality, whereas *Pentas* showed a more even distribution of responses across irrigation treatments and substrates.

Nitrogen dynamics. Nitrogen dynamics differed among substrates

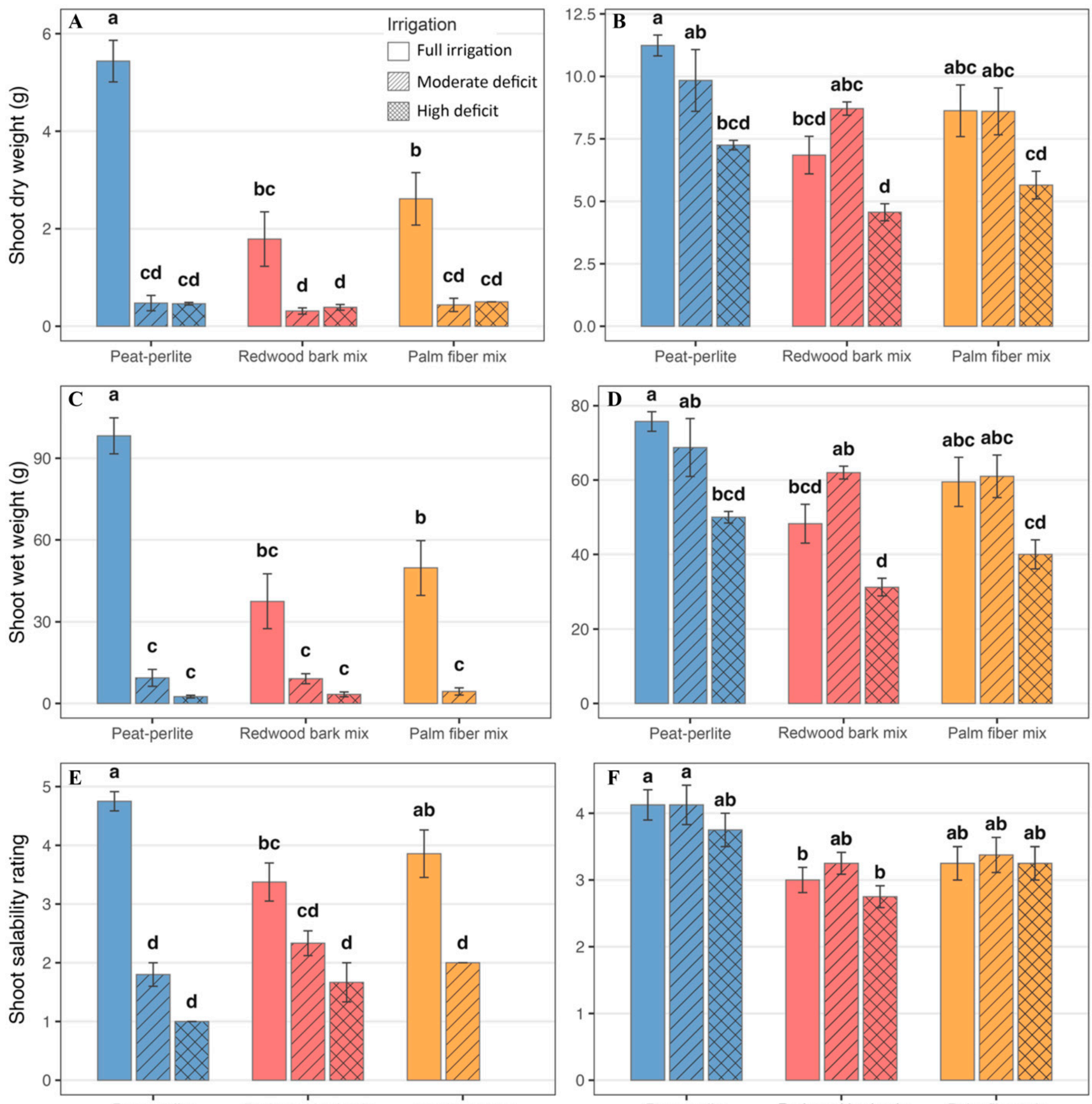

Fig. 5. Plant growth and shoot quality responses of *Impatiens* (left) and *Pentas* (right) grown in three substrates under deficit irrigation treatments. (A, B) Shoot dry weight. (C, D) Shoot fresh weight. (E, F) Shoot salability rating. Bars represent mean values ± the standard error. Different lowercase letters indicate statistically significant differences among treatments (Tukey's honestly significant difference, $P < 0.05$). Irrigation treatments correspond to volumes reported in Supplemental Table 1.

and irrigation treatments, with distinct patterns observed between species. In *Impatiens*, total shoot N concentrations ranged from 4.1% to 6.8% for peat–perlite, from 4.5% to 5.7% for the palm fiber mix, and from 3.8% to 4.4% for the redwood bark mix across irrigation levels (Fig. 7A). In *Pentas*, variation in shoot N concentration was lower (Fig. 7B, Supplemental Table 3). Peat–perlite ranged from 2.5% to 2.6% total N; the redwood bark mix, from 3.1% to 3.8%; and the palm fiber mix, from 2.8% to 3.3% across irrigation treatments. Overall, *Impatiens* exhibited greater shoot N concentrations than *Pentas*, with average values of 4.9% and 3.0%, respectively. In addition, shoots subjected to high-deficit treatments tended to have greater N concentrations than those of full-irrigation treatments, averaging 5.5% vs. 4.1% for *Impatiens* and 3.2% vs. 2.9% for *Pentas*. However, when expressed as total N accumulation, values were greater in *Pentas* than in *Impatiens* (0.23 g vs. 0.06 g on average) and in

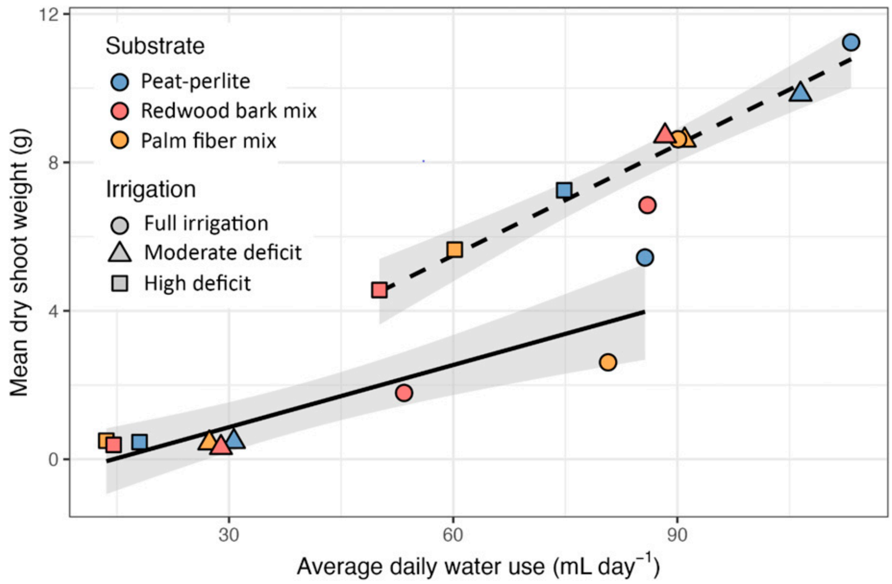

Fig. 6. Relationships between mean dry shoot weight and daily water use for *Impatiens* and *Pentas.* Colors represent the three substrates (peat–perlite, redwood bark mix, and palm fiber mix); symbols represent full, moderate-deficit, and high-deficit irrigation. Points represent mean dry shoot weight and average daily water use. Lines are fitted regressions for *Impatiens* (dashed line) and *Pentas* (solid line);shaded regions indicate 95% confidence intervals.

full irrigation treatments compared with high-deficit treatments (0.19 g vs. 0.10 g on average), reflecting greater biomass production.

A total of 2.4 g N was applied as fertilizer per container across all treatments (Fig. 7D, black outline; Supplemental Table 3). The amount released during the *Pentas* experiment and therefore available to enter the N balance ranged from 1.43 to 1.88 g N·container^{-1}, depending on substrate and irrigation treatment. The greatest fertilizer amount was released in the palm fiber mix (1.58–1.88 g·container^{-1}), whereas in peat–perlite the least was released, as indicated by the 0.90 to 0.98 g N recovered in the substrate at the end of the experiment. The redwood bark mix release was intermediate, with 0.75 to 0.90 g recovered. Residual fertilizer recovery tended to be slightly greater under high-deficit treatments, consistent with reduced release rates at lower substrate moisture.

Changes in substrate N content before and after the experiment illustrate differences in N dynamics observed in each substrate (Supplemental Table 3). In the palm fiber mix, N content increased from 2.62 g before the experiment to 3.13 g after, suggesting immobilization of N within the substrate. In contrast, peat–perlite showed a substantial decline in substrate N, from 2.32 g before the experiment to 1.35 g after. The redwood bark mix exhibited lower overall N content and a smaller decrease, from 1.11 g before the experiment to 0.92 g after.

Nitrogen balance calculations for *Pentas* indicate substantial differences among substrates in estimated unaccounted N (i.e., the residual between measured inputs and outputs) (Fig. 7C; Supplemental Table 3). The average unaccounted N was greatest in peat–perlite (2.21 g N·container^{-1}), followed by the redwood bark mix (1.55 g N·container^{-1}) and the palm fiber mix (0.97 g N·container^{-1}). However, when unaccounted N is expressed as a fraction of total N available to the system (calculated as unaccounted N divided by the sum of initial substrate N and fertilizer released during the experiment), peat–perlite and the redwood bark mix showed similar values (0.58 and 0.57, respectively), whereas the palm fiber mix was substantially less (0.22). The low fraction for the palm fiber mix is consistent with the aforementioned net N immobilization, which reduced unaccounted N by sequestering N within the substrate matrix. When evaluated by irrigation treatment, differences in unaccounted N were smaller, with average values of 1.56, 1.53, and 1.65 g N·container^{-1} for the high-deficit, moderate-deficit, and full-irrigation treatments, respectively. These results suggest that substrate properties had a stronger influence on N retention and loss than irrigation level, despite the greater irrigation leaching volumes observed in the full-irrigation treatment.

Discussion

Physicochemical properties. There are no universally accepted standards for the physical properties of container substrate. Suggested benchmark ranges provide a practical basis for evaluating substrate suitability and minimizing management requirements (Bilderback et al. 2005). In our study, bulk densities for peat–perlite and the redwood bark mix were less than the suggested range of 0.19 to 0.70 g·cm^{-3} (Table 1), whereas the palm fiber mix fell within it (0.22 g·cm^{-3}). Such low values are common in peat- and wood-based substrates and do not preclude commercial production (Barrett et al. 2016). The greater bulk density of the redwood bark mix relative to peat–perlite, despite its greater total porosity, reflects its greater particle density (Table 1), a pattern typical of wood-based materials in which the dense cell-wall structure coexists with a high proportion of interparticle void space (Gruda 2019).

The RAW for all three substrates fell near or marginally below the accepted range of 25% to 35% (Yeager et al. 1997), with the redwood bark mix closest to the lower bound. Plant growth nonetheless remained commercially acceptable in most treatment combinations for *Pentas*, and under full-irrigation for *Impatiens*, consistent with Chavez et al. (2008), who produced high-quality *Impatiens* and *Petunia* in alternative substrates with physical properties outside conventional target ranges under appropriate irrigation management.

The pH of the redwood bark mix (4.6) fell below the optimum range for most floricultural crops (5.3–6.5; Abad et al. 2001; Bailey and Nelson 1998), consistent with the acidic character typical of bark-based substrates (Gruda 2019). The coco coir component, although typically near neutral (Landis et al. 2014), did not offset this. Substrate pH can be adjusted with lime or dolomite if needed (Chong 2005; Vaughn et al. 2011), but no nutrient imbalances were observed in redwood

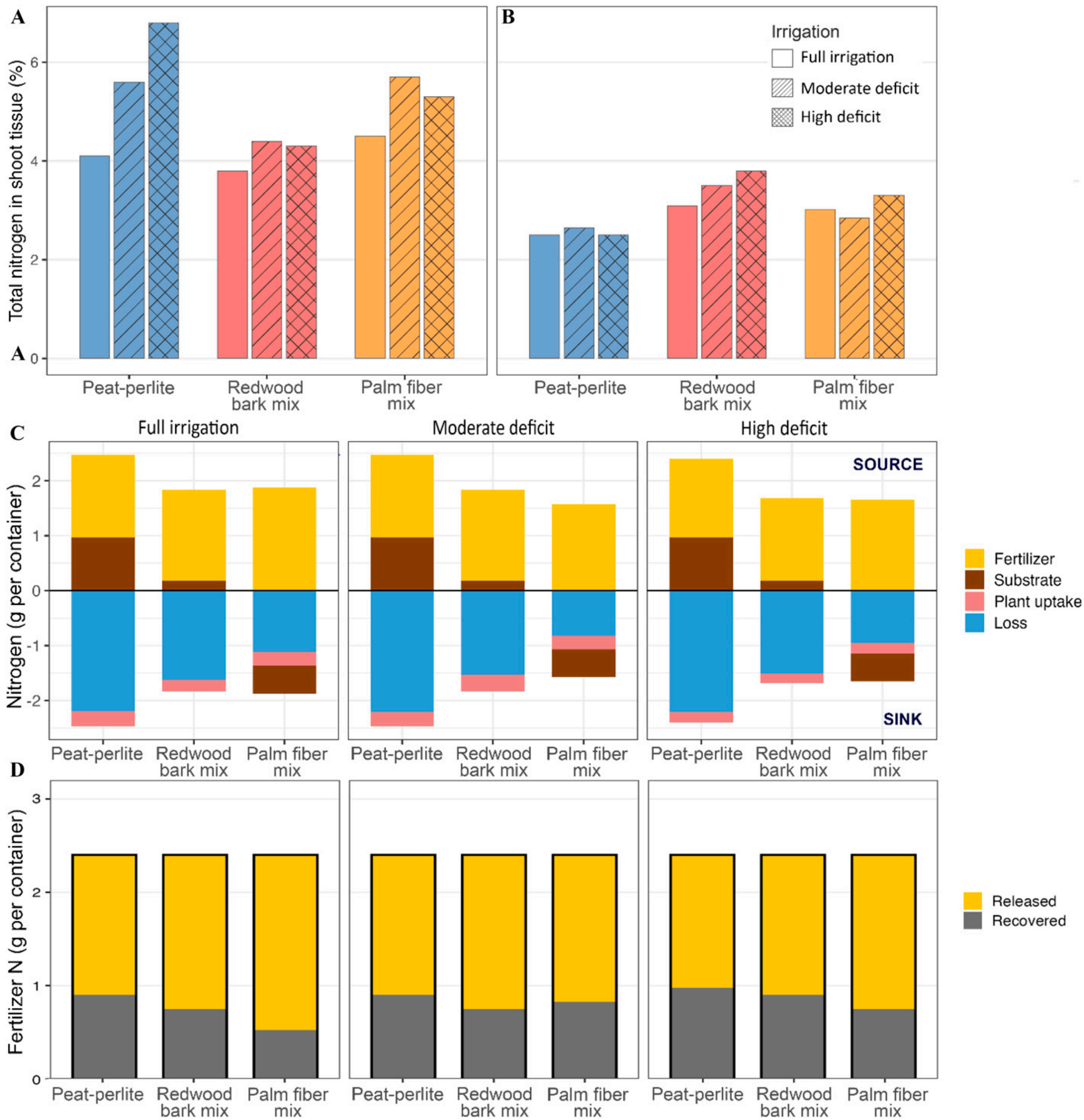

Fig. 7. Shoot tissue total nitrogen (TN) concentration (measured as a percentage of weight) for *Impatiens* (A) and *Pentas* (B), and N dynamics for *Pentas* across substrates and irrigation treatments. (C, D) *Pentas* N balance components, including N partitioning per container (fertilizer-derived N, net substrate N contribution, plant uptake, and unaccounted N) (C) and fertilizer N fractions (recovered and released, total applied is indicated by their sum, or the black solid bars outline) (D). Net substrate N contribution (C) was calculated as initial substrate N minus final substrate N. Positive values indicate that the substrate acted as a net N source, whereas negative values indicate net immobilization and are plotted as sinks. Unaccounted N was calculated by the difference between total sources and measured sinks, and likely represents leaching and gaseous losses. Bars represent mean values.

bark mix plants during the 8-week cycle. The EC for all substrates fell within or below the acceptable range of 0.75 to 2.0 dS·m^{-1} (Warncke 1995), indicating no salinity-related risk.

Substrate physical properties were characterized with the porometer method, which may not reflect in-container conditions at planting, because packing density, wetting history, and fill method alter pore structure. The van Genuchten curves indicate a tension greater than 50 kPa, near 30% VWC for peat–perlite; yet *Pentas* maintained moisture near this level throughout the high-deficit treatment and remained salable, suggesting that substrate behavior under field conditions differed from laboratory characterization.

Physical properties can change further during production through root growth, settling, particle breakdown, decomposition, and shrinkage, particularly in wood-based substrates over longer cycles (Jackson et al. 2009b). Visual inspection at experiment end showed structural breakdown in palm fiber mix containers, with wood chip fragments decomposed into finer organic material, although no measurable subsidence occurred in any substrate during the 8-week cycle. Longer term trials would be needed to evaluate stability, particularly for wood-based components. Overall, the physical and chemical properties of all three substrates, although not uniformly meeting established benchmarks, fell within ranges reported for commercially viable peat-alternative substrates (Barrett et al. 2016; Gruda 2019), and plant performance confirmed their practical suitability under appropriate irrigation management.

Water dynamics. The hydraulic behavior of the three substrates followed patterns consistent with their pore structure and composition. Wood-based substrates characteristically exhibit a coarser pore structure, with more large pores resulting in rapid drainage, early air entry, and reduced water retention compared with peat-based substrates (Fields et al. 2014a; Gruda 2019). The high air space of the redwood bark mix at container capacity (39.5%) exceeded the recommended range of 10% to 30% (Bilderback et al. 2005), consistent with a macropore-dominated structure that drains rapidly after irrigation. The RAW water in the redwood bark mix (25.4%) was nonetheless comparable to peat–perlite (24.8%), consistent with findings that wood-based substrates can sustain plant-accessible water within a defined tension range despite lower total water content (Fields et al. 2014a). Its steeper van Genuchten desaturation curve (n = 1.52 vs. 1.18 for peat–perlite) indicates this water is released within a narrow matric potential window near air entry. Fields et al. (2017, 2018) showed that substrates with lower unsaturated hydraulic conductivity in the dry range restrict water movement toward roots even when pore water is nominally present, a mechanism that likely contributed to the deficit-irrigation performance differences observed here, particularly in the *Impatiens* trial.

The limited lateral water redistribution in the redwood bark mix under single-emitter drip irrigation is consistent with the behavior of coarse materials: Wetting pattern geometry in container substrates is strongly influenced by pore structure and surface wettability (Liu et al. 2015), and coarser or hydrophobic materials restrict lateral redistribution from the drip point, directing water preferentially downward. Wettability is governed by initial moisture content, material hydrophobicity, and wetting agent presence (Fields et al. 2014a). The commercial peat–perlite used in our study contained a wetting agent that promotes lateral redistribution. The palm fiber mix, blended 1:1 with the same peat–perlite, retained intermediate rehydration from its peat–perlite content, and the redwood bark mix, a coarser, uncomposted wood-based material with no wetting agent, predictably showed the most limited redistribution, consistent with the wettability hierarchy reported for pine bark without wetting agents (Fields et al. 2014a). Particle size also matters. Fields et al. (2017) showed that finer hammer mill settings in wood-based substrates increase small-pore proportion and reduce preferential drainage, and the already fine, fibrous, triple-ground redwood bark used in our study could potentially be ground further to improve redistribution. Nurseries using coarse wood-based substrates under single-emitter drip irrigation may benefit from adding a wetting agent or switching to overhead or multiple-emitter systems, where rehydration depends less on lateral redistribution.

Despite these hydraulic differences under full irrigation, all three substrates produced comparable water use behavior under moderate- and high-deficit irrigation. This convergence suggests that palm fiber mix and redwood bark mix may serve as adequate replacements under deficit or moderate irrigation, particularly for drought-tolerant species for which the wetting agent and finer pore structure of peat–perlite are less consequential.

Plant growth and commercial quality. Plant growth and commercial quality were governed more by irrigation treatment and species identity than by substrate type, with substrate effects most apparent under full irrigation, for which differences in lateral water redistribution were greatest.

For *Impatiens*, commercial viability was restricted to the full-irrigation treatment across all substrates, with sharp biomass and quality declines under moderate- and high-deficit irrigation. This is consistent with the known sensitivity of *I. walleriana* to water deficit as a species native to humid East African environments (Augé et al. 2004; Kessler 2005; Milovančević et al. 2024), and with Chavez et al. (2008), who found *Impatiens* performance in alternative soilless substrates to be sensitive to water availability under limited irrigation. The broader temperature range during the *Impatiens* experiment (17.5–45 °C vs. 18–35 °C for *Pentas*) and greater evaporative demand likely accelerated the onset of water stress under deficit treatments, consistent with reports (Fields et al. 2017; Pagani et al. 2015) that high macroporosity, rapid-draining substrates can fail to sustain adequate water availability between irrigation events.

Within the full-irrigation treatment, the substrate hierarchy for both biomass and quality (peat–perlite > palm fiber mix > redwood bark mix) matches the differences in lateral water redistribution under single-emitter drip irrigation, as noted in the previous subsection. The wetting agent for peat–perlite likely achieved the most uniform root-zone wetting and the steepest rehydration-to-irrigation relationship (Fig. 4). Fields et al. (2017, 2018) showed that substrates with lower unsaturated hydraulic conductivity in the dry range constrain plant water access even when total container water content is nominally sufficient, which likely explains the gap between peat–perlite and the alternatives under full irrigation. This effect was more pronounced in *Impatiens* than *Pentas*, reflecting the former's greater sensitivity to uneven water distribution.

Pentas maintained commercial viability across most substrate and irrigation combinations, reflecting greater inherent drought tolerance than *Impatiens*, consistent with its adaptation to warm, high evaporative demand conditions (Klock-Moore and Broschat 2001; Whipker and Veazie 2023). The same substrate hierarchy held in *Impatiens*, but with smaller differences, except for an increase in redwood bark mix biomass from full- to moderate-deficit irrigation, a pattern Fields et al. (2018) attributed to excessive drainage reducing plant-available water under high-frequency wet-treatment irrigation in coarse substrates. Jackson et al. (2008) similarly found pine tree substrate and peat-lite produced comparable *Poinsettia* growth when fertilizer rates were sufficient, supporting the commercial viability of redwood bark mix for *Pentas* under managed-deficit irrigation when water and nutrient supply are optimized.

The positive relationship between daily water use and shoot dry weight (Fig. 6) confirms that biomass accumulation scaled with water consumption in both species, with a steeper slope for *Pentas* reflecting greater water use efficiency consistent with its adaptation to drier conditions.

Nitrogen dynamics. Shoot N concentrations were within recommended ranges for both species [3.64%–5.83% for *Impatiens* (Bryson et al. 2014) and 3.22%–4.43% for *Pentas* (Whipker et al. 2020)], except for *Pentas* in peat–perlite, where concentrations fell marginally below the lower bound regardless of irrigation treatment. The absence of visible deficiency symptoms or reduced salability suggests this lower bound may be conservative under the fertilization program used. Greater tissue N under deficit irrigation relative to full irrigation reflects a concentration effect as biomass declined with decreasing water supply, a well-documented response in container ornamental production (Romero et al. 2006).

Substrate N dynamics diverged substantially among substrates and were the dominant driver of N fate in this system. The palm fiber mix was the only substrate to show a net increase in substrate N, indicating net microbial immobilization, whereas peat–perlite and the redwood bark mix both showed net declines, consistent with net mineralization. The immobilization in the palm fiber mix matches the high C:N ratio characteristic of lignocellulosic materials, which favors microbial N uptake over plant N availability (Harris et al. 2020; Jackson et al., 2009a; Maher et al. 2008). Uke et al. (2021) showed that oil palm trunk fiber specifically drives proliferation of lignocellulose-degrading fungi (e.g., *Trichoderma* and *Trichocladium*), causing N immobilization and deficiency in container-grown crops, providing a direct microbial mechanism for the pattern observed in our study. Jackson et al. (2009a) similarly found N immobilization greatest in pine tree substrate relative to peat-lite and aged pine bark, increasing with fertilizer rate and correlating with carbon dioxide efflux, confirming that high-C:N wood-based materials consistently compete with plants for mineral N, although lignification not just the C:N ratio affects degradation suitability (Wang et al. 2024).

The net mineralization in peat–perlite released substrate N into the available pool; however, because plant N uptake was similar across all three substrates (~0.23–0.24 g N·container^{-1}), this larger availability did not translate into more plant uptake and likely entered leachate or gaseous pathways instead. Unaccounted N fractions were substantially greater in peat–perlite (0.58) and the redwood bark mix (0.57) than in the palm fiber mix (0.22), consistent with Chen et al. (2001), who reported up to 50% of applied fertilizer N may leach from container nursery systems, and Colangelo and Brand (2001), who documented substantial nitrate leaching beneath containerized nursery crops under trickle irrigation, the same method used in our study.

Irrigation treatment had a comparatively minor effect on N dynamics relative to substrate, with unaccounted N varying less than 0.1 g·container^{-1} across irrigation levels. This decoupling of fertilizer release and N losses is a key finding: Peat–perlite showed the smallest fertilizer release yet the greatest unaccounted N, driven by substrate mineralization rather than fertilizer release, whereas the palm fiber mix released the most fertilizer yet showed the least unaccounted N through immobilization. This decoupling is consistent with that noted by Oki et al. (2021), who found substrate organic matter dynamics, not fertilizer management, drove N fate in a system-level N balance study of California, USA, container production. Partitioning this unaccounted N between gaseous denitrification and leaching could not be determined, as leachate N was not measured, although observed drainage volumes suggest leaching was the more likely pathway.

Our results carry direct practical implications. The high N immobilization capacity of the palm fiber mix suggests that standard fertilizer rates designed for peat-based substrates may be insufficient to maintain adequate plant-available N over longer production cycles, even though no deficiency was observed in our 8-week study. Additional substrate-specific fertility programs with elevated N rates or preplant amendments may be warranted. Conversely, the greater unaccounted N in the redwood bark mix and especially peat–perlite may increase the risk of N contamination to surface and groundwater—a relevant consideration under nutrient discharge regulations increasingly stringent for California, USA, nurseries and greenhouses.

Integrated performance and economic comparison. Evaluating peat-alternative substrates requires balancing performance, economic, and environmental criteria simultaneously, and no single material optimizes all dimensions (Barrett et al. 2016). Our multicriteria comparison (Fig. 8) illustrates this directly: The three substrates showed distinct, nonoverlapping performance profiles across growth, water use, and N metrics, with no substrate dominating every axis.

The clearest axis of differentiation was the trade-off between biomass productivity and N conservation. Peat–perlite produced the greatest shoot dry weight, salability, and water use efficiency, but also the greatest unaccounted N, consistent with prior findings that peat-based substrates generate disproportionate N losses relative to plant uptake (Chen et al. 2001; Colangelo and Brand 2001; Oki et al. 2021). The palm fiber mix showed the least amount of unaccounted N and greatest residual substrate N, with intermediate biomass and water use performance. The redwood bark mix ranked lowest for biomass and rehydration, consistent with its high macroporosity and limited lateral water redistribution (as described earlier), but maintained commercially viable *Pentas* quality across all irrigation levels.

Species sensitivity governed which trade-off mattered most in practice. For water-sensitive *Impatiens*, the hydraulic advantages of peat–perlite were critical, and neither alternative substrate produced commercially acceptable plants under deficit irrigation. For drought-tolerant *Pentas*, despite different growing conditions, the performance gap among substrates was smaller, shifting the choice

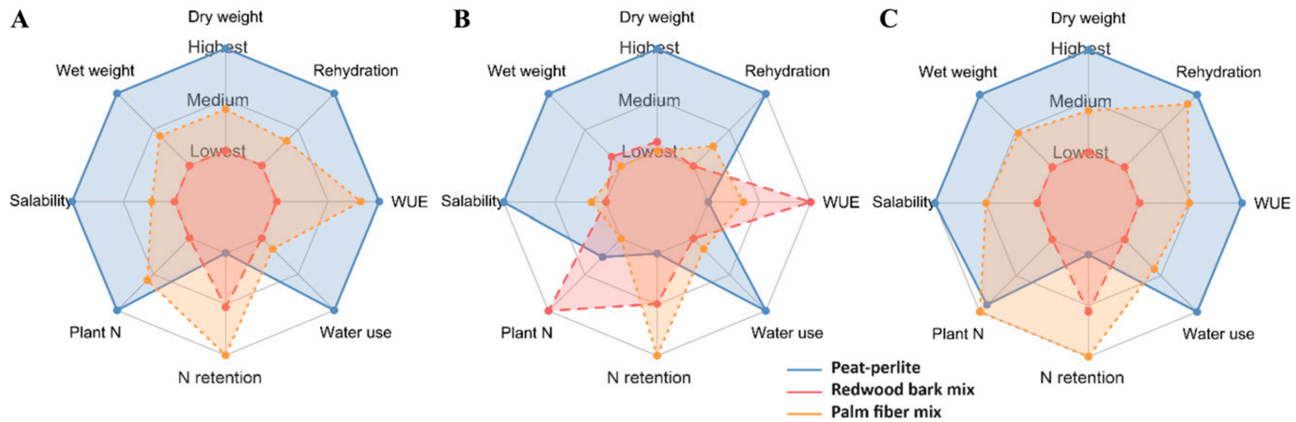

Fig. 8. Radar plots comparing substrate performance across plant growth, nitrogen (N) dynamics, and water use metrics for the full (A), moderate-deficit (B), and high-deficit (C) irrigation regimes for *Pentas*. Axes represent normalized relative responses (scaled from lowest to highest) for dry shoot weight, rehydration, water use efficiency (WUE; WUE = Dry weight ÷ Water use), water use, N retention, plant N uptake (measured in grams), salability, and wet shoot weight. Polygons illustrate the multicriteria profiles of peat–perlite, redwood bark mix, and palm fiber mix substrates, highlighting trade-offs among biomass production, water use, and N cycling.

toward cost and environmental criteria rather than productivity alone, consistent with the observation by Barrett et al. (2016) that growing-media performance must be evaluated relative to the target crop and production system.

Economically, a palm fiber mix carries a lower material cost ($78/m^3; W. Darlington, personal communication) than peat–perlite ($131·m^{-3}) and the redwood bark mix (~$105·m^{-3}; ASG Developments Inc, D. White, personal communication). For *Pentas* and similarly drought-tolerant ornamentals, this cost advantage may favor a redwood bark mix when paired with overhead or multiple-emitter irrigation that mitigate its limited lateral redistribution. The lower N losses of the palm fiber mix may carry additional value where nutrient discharge regulations apply increasingly relevant for California, USA, nurseries and greenhouses.

These findings should be interpreted in light of the experimental design. The study was short (8 weeks), a single fertilizer rate was applied uniformly, and mixing ratios differed by substrate (e.g., 70:30 redwood bark:-coco coir, 50:50 palm fiber:peat–perlite). Longer term studies, substrate-specific fertility rates accounting for N immobilization in wood-based materials, optimized mixing ratios, and trials across a broader range of floricultural species would help characterize the commercial suitability of these alternatives. Measuring leachate N concentration in future trials would also allow partitioning of unaccounted N between leaching and denitrification.

Conclusion

We evaluated two peat-alternative substrates—a peat-reduced palm fiber–peat mix and a peat-free redwood bark–coco coir blend—relative to a conventional peat–perlite mix under different irrigation regimes. The three substrates differed in their physical and hydraulic properties. Peat–perlite exhibited the greatest container capacity and maintained a greater moisture content across a range of irrigation regimes, making it well suited for growing plants with different water demands under variable (even deficit) irrigation management. The palm fiber–peat mix (50:50) showed intermediate water-holding behavior, whereas the redwood bark–coir (70:30) was characterized by high macroporosity, low container capacity, and limited lateral water redistribution under single-emitter drip irrigation.

These hydraulic differences had direct implications for plant performance, particularly under deficit irrigation and for water-sensitive species. Both the palm fiber mix and the redwood bark mix produced plant growth and commercial quality comparable to peat–perlite for *Pentas* under most irrigation treatments, with greater differences emerging among irrigation treatments within the same substrate than across substrates. *Impatiens*, which is highly sensitive to water deficit, showed steep biomass declines under moderate-deficit and high-deficit irrigation regimes across all substrates, but indicated significantly greater performance for peat–perlite compared with the other substrates only under the full-irrigation treatment. With the moderate-deficit and high-deficit treatments, most plants died, making substrate hydraulic differences less distinguishable under those conditions. The redwood bark mix showed limited lateral water redistribution under single-emitter drip, which can be a concern with this type of irrigation system.

Nitrogen immobilization was observed in the palm fiber mix during the production cycle, consistent with the high C:N ratio of lignocellulosic materials, and visual evidence of particle breakdown was present by the end of the experiment. These findings suggest that additional fertility management and longer term monitoring of substrate stability are warranted for extended production cycles.

Overall, our palm fiber mix shows genuine promise as a locally sourced, peat-reduced alternative for container production, particularly for species with moderate water sensitivity. A redwood bark mix may be better suited to overhead or multiple-emitter irrigation systems, where lateral water distribution is less critical.

References cited

Abad M, Noguera P, Bures S. 2001. National inventory of organic wastes for use as growing media for ornamental potted plant production: Case study in Spain. Bioresour Technol. 77(2):197–200. https://doi.org/10.1016/s0960-8524(00)00152-8.

Augé RM, Sylvia DM, Park S, Buttery BR, Saxton AM, Moore JL, Cho K. 2004. Partitioning mycorrhizal influence on water relations of *Phaseolus vulgaris* into soil and plant components. Can J Bot. 82(4): 503–514. https://doi.org/10.1139/b04-020.

Aurdal SM. 2025. The persistent challenge of alternatives to peat in container-based horticulture: A historical review of the field of growing media. Front Hortic. 4:1657037. https://doi.org/10.3389/fhort.2025.1657037.

Bailey DA, Nelson PV. 1998. Managing micronutrients in the greenhouse. Horticulture information leaflet no. 553. North Carolina State University, Raleigh, NC, USA.

Barrett GE, Alexander PD, Robinson JS, Bragg NC. 2016. Achieving environmentally sustainable growing media for soilless plant cultivation systems: A review. Sci Hortic. 212:220–234. https://doi.org/10.1016/j.scienta.2016.09.030.

Bilderback TE, Warren SL, Owen JS Jr, Albano JP. 2005. Healthy substrates need physicals too!. HortTechnology. 15(4): 747–751. https://doi.org/10.21273/HORTTECH.15.4.0747.

Brumfield RG, Kenny LB, DeVincentis AJ, Koeser AK, Verlinden S, Both AJ, Bi G, Lovell ST, Stewart JR. 2018. Analysis of economic and social costs of growing *Petunia ×hybrida* in a greenhouse production system using alternative containers. HortScience. 53(8):1179–1185. https://doi.org/10.21273/HORTSCI13044-18.

Bryson GM, Mills HA, Sasseville DN, Jones JB, Barker AV. 2014. Plant analysis handbook III: A guide to sampling, preparation, analysis, interpretation and use of results of agronomic and horticultural crop plant tissue. Micro-Macro Publishing, Athens, GA, USA.

Caron J, Michel J-C. 2015. Overcoming physical limitations in alternative growing media with and without peat. Acta Hortic. 1168:413–422. https://doi.org/10.17660/ActaHortic.2017.1168.53.

Ceglie FG, Bustamante MA, Ben Amara M, Tittarelli F. 2015. The challenge of peat substitution in organic seedling production: Optimization of growing media formulation through mixture design and response surface analysis. PLoS One. 10(6): e0128600. https://doi.org/10.1371/journal.pone.0128600.

Chavez W, Di Benedetto A, Civeira G, Lavado R. 2008. Alternative soilless media for growing *Petunia ×hybrida* and *Impatiens walleriana*: Physical behavior, effect of fertilization and nitrate losses. Bioresour Technol. 99(17):8082–8087. https://doi.org/10.1016/j.biortech.2008.03.063.

Chen J, Huang Y, Caldwell RD. 2001. Best management practices for minimizing nitrate leaching from container-grown nurseries. Sci World J. 1(Suppl 2):96–102. https://doi.org/10.1100/tsw.2001.99.

Choi HS, Zhao Y, Dou H, Cai X, Gu M, Yu F. 2018. Effects of biochar mixtures with pine bark–based substrates on growth and development of horticultural crops. Hortic Environ Biotechnol. 59(3):345–354. https://doi.org/10.1007/s13580-018-0035-x.

Chong C. 2005. Experiences with wastes and composts in nursery substrates. HortTechnology. 15(4):739–747. https://doi.org/10.21273/HORTTECH.15.4.0739.

Colangelo DJ, Brand MH. 2001. Nitrate leaching beneath a containerized nursery crop receiving trickle or overhead irrigation. J Environ Qual. 30(5):1564–1574. https://doi.org/10.2134/jeq2001.3051564x.

de Mendiburu F. 2023. agricolae: Statistical Procedures for Agricultural Research. R package version 1.3-7.

Fields JS, Fonteno WC, Jackson BE. 2014a. Hydration efficiency of traditional and alternative greenhouse substrate components. HortScience. 49(3):336–342. https://doi.org/10.21273/HORTSCI.49.3.336.

Fields JS, Fonteno WC, Jackson BE, Heitman JL, Owen JS. 2014b. Hydrophysical properties, moisture retention, and drainage profiles of wood and traditional components for greenhouse substrates. HortScience. 49(6):827–832. https://doi.org/10.21273/HORTSCI.49.6.827.

Fields JS, Owen JS Jr, Altland JE, van Iersel MW, Jackson BE. 2018. Soilless substrate hydrology can be engineered to influence plant water status for an ornamental containerized crop grown within optimal water potentials. J Am Soc Hortic Sci. 143(4):268–281. https://doi.org/10.21273/JASHS04251-17.

Fields JS, Owen JS Jr, Scoggins HL. 2017. The influence of substrate hydraulic conductivity on plant water status of an ornamental container crop grown in suboptimal substrate water potentials. HortScience. 52(10):1419–1428. https://doi.org/10.21273/HORTSCI11987-17.

Fonteno WC, Bilderback TE. 1993. Impact of hydrogel on physical properties of coarse-structured horticultural substrates. J Am Soc Hortic Sci. 118(2):217–222. https://doi.org/10.21273/JASHS.118.2.217.

Fonteno W, Hardin C, Brewster J. 1995. Procedures for determining physical properties of horticultural substrates using the NCSU Porometer. Horticultural Substrates Laboratory, North Carolina State University, Raleigh, NC, USA.

Gomis MP, Perez-Murcia MD, Barber X, Martinez-Sabater E, Moral R, Bustamante MÁ. 2022. Development and validation of alternative palm-derived substrates for seedling production. Agronomy. 12(6): 1377. https://doi.org/10.3390/agronomy12061377.

Gruda N. 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy. 9(6):298. https://doi.org/10.3390/agronomy9060298.

Gruda NS. 2022. Advances in soilless culture and growing media in today's horticulture: An editorial. Agronomy. 12(11): 2773. https://doi.org/10.3390/agronomy12112773.

Harris CN, Dickson RW, Fisher PR, Jackson BE, Poleatewich AM. 2020. Evaluating peat substrates amended with pine wood fiber for nitrogen immobilization and effects on plant performance with container-grown petunia. HortTechnology. 30(1):107–116. https://doi.org/10.21273/HORTTECH04526-19.

Jackson BE, Fonteno WC. 2015. An overview of new and revised methodologies and technologies in substrate analysis and characterization. Acta Hortic. 1168: 365–376. https://doi.org/10.17660/ActaHortic.2017.1168.47.

Jackson BE, Wright RD, Alley MM. 2009a. Comparison of fertilizer nitrogen availability, nitrogen immobilization, substrate carbon dioxide efflux, and nutrient leaching in peat-lite, pine bark, and pine tree substrates. HortScience. 44(3):781–790. https://doi.org/10.21273/HORTSCI.44.3.781.

Jackson BE, Wright RD, Barnes MC. 2008. Pine tree substrate, nitrogen rate, particle size, and peat amendment affects poinsettia growth and substrate physical properties. HortScience. 43(7):2155–2161. https://doi.org/10.21273/HORTSCI.43.7.2155.

Jackson BE, Wright RD, Seiler JR. 2009b. Changes in chemical and physical properties of pine tree substrate and pine bark during long-term nursery crop production. HortScience. 44(3):791–799. https://doi.org/10.21273/HORTSCI.44.3.791.

Kessler JR. 2005. Greenhouse production of Impatiens. Alabama Cooperative Extension System, Huntsville, AL, USA.

Kingston PH, Scagel CF, Bryla DR, Strik B. 2017. Suitability of sphagnum moss, coir, and Douglas fir bark as soilless substrates for container production of highbush blueberry. HortScience. 52(12): 1692–1699. https://doi.org/10.21273/HORTSCI12374-17.

Klock-Moore KA, Broschat TK. 2001. Effect of four growing substrates on growth of ornamental plants in two irrigation systems. HortTechnology. 11(3):456–460. https://doi.org/10.21273/HORTTECH.11.3.456.

LA Sanitation. 2026. California Senate Bill 1383 (SB 1383) preparation and city of LA Organics ordinances. https://sanitation.lacity.gov/san/faces/home/portal/s-lsh-wwd/s-lsh-wwd-s/s-lsh-wwd-s-o/s-lsh-wwd-s-o-frp/s-lsh-wwd-s-o-frp-csb1383?_adf.ctrl-state=umqa84od2_1&_afrLoop=1605589484415936&_afrWindowMode=0&_afrWindowId=null#!%40%40%3F_afrWindowId%3Dnull%26_afrLoop%3D1605589484415936%26_afrWindowMode%3D0%26_adf.ctrl-state%3Dumqa84od2_5. [accessed 15 Jul 2026].

Landis TD, Jacobs DF, Wilkinson KM, Luna T. 2014. Growing media tropical nursery manual: A guide to starting and operating a nursery for native and traditional plants. Agric Handb. 732:101–122.

Liu Z, Li P, Hu Y, Wang J. 2015. Wetting patterns and water distributions in cultivation media under drip irrigation. Comput Electron Agric. 112:200–208. https://doi.org/10.1016/j.compag.2015.01.003.

Maher M, Prasad M, Raviv M. 2008. Organic soilless media components, p 459–504. In: Raviv M, Lieth JH (eds). Soilless culture: Theory and practice. Elsevier, Amsterdam, Netherlands.

Mahmoud ER, Aly HM, Hassan NA, Aljabri A, Khan AL, El-Labban HF. 2024. Utilizing date palm leaf biochar for simultaneous adsorption of Pb (II) and iodine from aqueous solutions. Processes. 12(7):1370. https://doi.org/10.3390/pr12071370.

Milovančević M, Trifunović-Momčilov M, Radulović O, Milošević S, Subotić A. 2024. Drought stress effects and ways for improving drought tolerance in *Impatiens walleriana* Hook. f.: A review. Horticulturae. 10(9):903. https://doi.org/10.3390/horticulturae10090903.

Oki LR, Evans RY, Horwath WR, Pitton BJL. 2021. A system nitrogen balance for container plant production. California Department of Food and Agriculture Fertilizer Research and Education Program, University of California, Davis, CA, USA.

Pagani A, Molinari J, Lavado R, Di Benedetto A. 2015. Behavior of *Impatiens walleriana* Hook. f. in alternative pot substrates: Mechanisms involved and research perspectives. J Plant Nutr. 38(14):2185–2203. https://doi.org/10.1080/01904167.2014.988357.

Pooyeh F, Peyvast G, Olfati JA. 2012. Growing media including palm waste in soilless culture of cucumber. Int J Veg Sci. 18(1):20–28. https://doi.org/10.1080/19315260.2011.568599.

Romero FR, Taber HG, Gladon RJ. 2006. Nitrogen source and concentration affect growth and performance of bedding-plant *Impatiens*. J Plant Nutr. 29(7):1315–1326. https://doi.org/10.1080/01904160600767658.

Schulker BA, Jackson BE, Fonteno WC, Heitman JL, Albano JP. 2020. Comparison of water capture efficiency through two irrigation techniques of three common greenhouse soilless substrate components. Agronomy. 10(9):1389. https://doi.org/10.3390/agronomy10091389.

Thiessen M, Fields JS, Abdi D, Beasley J. 2023. Sugarcane bagasse is an effective soilless substrate amendment in quick-turn *Osteospermum* production. HortScience. 58(10):1170–1177. https://doi.org/10.21273/HORTSCI17286-23.

Uke A, Nakazono-Nagaoka E, Chuah J-A, Ahmad Zain N-A, Amir H-G, Sudesh K, Zainal Abidin NZHA, Hashim Z, Kosugi A. 2021. Effect of decomposing oil palm trunk fibers on plant growth and soil microbial community composition. J Environ Manag. 295:113050. https://doi.org/10.1016/j.jenvman.2021.113050.

Vaughn SF, Deppe NA, Palmquist DE, Berhow MA. 2011. Extracted sweet corn tassels as a renewable alternative to peat in greenhouse substrates. Ind Crops Prod. 33(2):514–517. https://doi.org/10.1016/j.indcrop.2010.10.034.

Wang NY, He Y, Zhao KQ, Lin X, He X, Chen AW, Wu GY, Zhang JC, Yan BH, Luo L, Xu DJ. 2024. Greenhouse gas emission characteristics and influencing factors of agricultural waste composting process: A review. J Environ Manag. 354:120337. https://doi.org/10.1016/j.jenvman.2024.120337.

Warncke DD. 1995. Recommended test procedures for greenhouse growth media. University of Delaware Agric Expt Stn Coop Bull 493.

Whipker B, Cockson P, Henry JE, Owen WG. 2020. Nutritional Monitoring Series: *Pentas (Pentas lanceolata). e-GRO Nutritional Monitoring Series, Vol. 3, No. 11, May 2020.*

Whipker B, Veazie P. 2023. *Pentas* growth response to nitrogen concentrations. Acta Hortic. 1389:263–270. https://doi.org/10.17660/ActaHortic.2024.1389.30.

Wright RD, Browder JF. 2005. Chipped pine logs: A potential substrate for greenhouse and nursery crops. HortScience. 40(5):1513–1515. https://doi.org/10.21273/HORTSCI.40.5.1513.

Xiong J, Tian Y, Wang J, Liu W, Chen Q. 2017. Comparison of coconut coir, rockwool, and peat cultivations for tomato production: Nutrient balance, plant growth and fruit quality. Front Plant Sci. 8:1327. https://doi.org/10.3389/fpls.2017.01327.

Yeager T, Gilliam C, Bilderback TE, Fare D, Niemiera A, Tilt K. 1997. Best management practices: Guide for producing container-grown plants. Southern Nursery Association, Atlanta, GA, USA.