Replacing Conventional Nursery Crop Nutrient Inputs with Vermicompost for Container Production of *Hibiscus moscheutos* L. ‘Luna Blush’

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Abstract. Vermicomposting of pig manure is a waste management approach that has been shown to be economically and technologically feasible and yields a value-added end product, vermicompost (VC), that contains plant-available nutrients. The objective of this study was to determine if conventional nursery crop inputs could be replaced by commercially available VC (derived from pig manure) for production of *Hibiscus moscheutos* ‘Luna Blush’ L. (hibiscus). Hibiscus was grown in 3.8-L containers containing pine bark amended with 11% sand (by vol.), 1.8 kg·m⁻³ dolomitic limestone, and 0.9 kg·m⁻³ micronutrient package (PBS) or pine bark amended with 20% VC (by vol.) (20VC). Plants were topdressed with one of three controlled-release fertilizers (CRF) containing only nitrogen (N); N and potassium (K); or N, phosphorus (P), and K. The four treatments included PBS with 17–6–12 (PBS + NPK), 20VC with 17–6–12 (20VC + NPK), 20VC with 17–0–12 (20VC + NK), and 20VC with 17–0–0 (20VC + N). The PBS + NPK treatment, which was supplied with conventional nursery crop nutrient inputs (limestone, sulfated micronutrients, and CRF containing NPK), served as the control treatment to represent the industry standard. All treatments were irrigated to maintain a leaching fraction (LF = volume leached ÷ volume applied) of 0.24. Daily inorganic nitrogen (IN-N) and dissolved reactive phosphorus (DRP) effluent contents were determined. Plants were harvested at 35 and 56 d after potting (DAP). Total plant nutrient contents of P, calcium (Ca), magnesium (Mg), and sulfur (S), iron (Fe), manganese, zinc (Zn), copper (Cu), and boron (B) were equivalent or greater for all three 20VC treatments compared with PBS + NPK. However, total plant K content of 20VC + N was less than 20VC + NPK, 20VC + NK, and PBS + NPK. Regardless of lower K content in the 20VC + N treatment, all three 20VC treatments had equivalent total plant dry weight and number of flowers. Furthermore, all three 20VC treatments averaged 58% and 40% greater plant dry weight than PBS + NPK at 35 and 56 DAP, respectively, and 93% more flowers than PBS + NPK at 56 DAP. All three 20VC treatments had similar IN-N and DRP effluent contents. However, the three 20VC treatments averaged 4.3× more IN-N effluent content and 59× DRP effluent content than PBS + NPK. The nutrient use efficiencies for all treatments were similar, in which nitrogen use efficiency ranged from 9% to 15% and phosphorus use efficiency ranged from 7% to 12%. In conclusion, this source of VC provided equivalent or greater P, Ca, Mg, S, Fe, Zn, and Cu but less K for plant uptake compared with the industry standard (control) treatment and produced larger plants with more flowers than the control. This suggests that dolomitic lime, sulfated micronutrients, and P can be eliminated as substrate additives.

Vermicomposting is an economically and technologically feasible organic waste management approach that yields the value-added product vermicompost (VC) or worm castings (Albanell et al., 1988; Atiyeh et al., 2000; Edwards, 1995; Hartenstein and Hartenstein, 1981). During the process, earthworms and microorganisms stabilize organic waste in an aerobic, moist, nonthermophilic environment (Sylvia et al., 2005). The resulting product has been successfully marketed as a pine bark amendment to progressive nursery crop producers (Bob Binkley, CEO, Nature-Works Organics, Advance, NC, personal communication). Benefits to growers include greater plant growth and flower production (Arancon et al., 2008; Hidalgo and Harkess,

2002), improved water use efficiency of production (McGinnis et al., 2005), and sufficient levels of some plant-available nutrients (Handreck, 1986).

Several studies reported increased plant growth when VC was amended to a soilless substrate at a rate of ≈20% (by vol.) when sufficient plant nutrients were provided through fertilizer. Hidalgo and Harkess (2002) reported increased growth and flower production of 70-d-old chrysanthemum [*Dendranthema × grandiflora* (Ramat.) Kitam. ‘Miramar’] grown in 25% VC [derived from sheep manure (*Ovis* sp.)] compared with a control (0% VC) when a complete liquid fertilizer [300 mg·L⁻¹ nitrogen (N)] was regularly applied to all treatments. Similarly,

42-d-old petunia (*Petunia × hybrida* Vilm.) had greater dry shoot weight and flower number when grown in 20% VC [derived from cattle manure (*Bos* sp.)] compared with a control (0% VC) [complete liquid fertilizer (200 mg·L⁻¹ N) applied to all treatments] (Arancon et al., 2008). Additionally, 42-d-old tomato (*Lycopersicon esculentum* Mill. ‘Rutgers’) and marigold (*Tagetes patula* L. ‘Queen Sophia’) transplants had greater dry shoot weights when grown in 20% VC [derived from pig manure (*Sus* sp.)] compared with a control (0% VC) [complete liquid fertilizer (200 mg·L⁻¹ N) applied to all treatments starting 14 d after germination] (Bachman and Metzger, 2008). Atiyeh et al. (2002) and Bachman and Davis (2000) have reported similar findings with 121-d-old marigold ‘Queen Sophia’ and 112-d-old *Magnolia virginiana* L. liners, respectively, when grown in VC (derived from pig manure) amended substrates. Because sufficient fertilizer nutrients were provided, Sprengel-Leibig’s law of the minimum (Epstein and Bloom, 2005) suggests that additional nutrients provided by VC were not solely responsible for increased plant growth. The exact mechanism that causes increased plant growth associated with VC is unclear. Nevertheless, several researchers have suggested it may be the result of synergistic effects of a variety of factors, including improved substrate physical properties, greater availability of plant nutrients, influence of hormone-like or humic substances, and the presence of beneficial microorganisms (Arancon et al., 2004; Tomati and Galli, 1995).

Regardless of the degree in which nutrients supplied by VC increase crop growth (or not), plant-available nutrients provided by VC should be able to benefit containerized crop production systems by reducing or eliminating fertilizer nutrient inputs from conventional fertilizer sources. Evidence that plant-available nutrients are associated with VC was shown with increasing extractable nutrient concentrations of substrates amended with increasing rates of VC (Bachman and Metzger, 2007; Hidalgo et al., 2006). These results demonstrate plant-available nutrients are associated with VC but do not quantify or estimate plant-available nutrient content. Evidence that plant-available nutrients are provided by VC was also demonstrated with increased growth of plants produced in unfertilized VC (derived from pig and cattle manure) amended substrates compared with plants produced in an unfertilized control (0% VC) (Atiyeh et al., 2001; Bachman and Metzger, 2008; Hidalgo et al., 2006). However, VC will not supply sufficient quantities of all plant essential nutrients, because plants grown in unfertilized VC (derived from pig and cattle manure) amended substrates produced very little biomass (Hidalgo et al., 2006) and/or less biomass compared with plants grown in a fertilized control (0% VC) (Atiyeh et al., 2001; Bachman and Metzger, 2008). The specific growth-limiting nutrient(s) were not investigated by these studies.

Plant-available nutrient content (N in particular) and rate of nutrient release can be predicted from mineralization study results, because N from compost (including vermicompost) is continually released through mineralization processes (Baldwin and Greenfield, 2006). However, because mineralization experiments are lengthy and labor-intensive, nutrient availability coefficients, the fraction of the total nutrient concentration estimated to be plant-available, are often used as guidelines to predict the available nutrient content from a composted material (Baldwin and Greenfield, 2006).

Identification of growth-limiting nutrients supplied by various sources of VC was conducted by Handreck (1986). Handreck (1986) evaluated eight sources of VC amended at 30% to pine bark for their ability to supply plant-available nutrients. Sufficient phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum was supplied by all sources for production of 59-d-old *Matthiola incana* L. (stock) with the exception of one VC source in which high levels of Zn resulted in poor plant growth. The ability of VC to provide sufficient potassium (K) and sulfur (S) depended on the waste material from which the VC was derived, and sufficient N was not provided by any of the eight VC sources (Handreck, 1986). Results of a laboratory mineralization study of vermicomposted pig manure (McGinnis, 2010) supported Handreck's results that N supplied by VC is growth-limiting. McGinnis (2010) estimated a 20% VC (by vol.) amended pine bark substrate provided ≈ 300 mg per 3.8-L container plant-available N over 8 weeks. This is less than 10% N that would be commonly applied (3–5 g N/3.8-L container) as a controlled-release fertilizer (CRF). Based on these results, VC will not provide sufficient N necessary to maximize growth of

containerized crops. Therefore, a supplemental N source is necessary to maximize production of container growth crops produced in a VC amended substrate.

We hypothesized that pine bark amended with VC derived from pig manure can provide all nutrients to maximize nursery crop growth with the exception of N and possibly K and S. The objectives of this study were to determine which conventional nursery crop nutrient inputs (dolomitic limestone, sulfated micronutrients, and CRF with NPK) could be substituted with VC for production of *Hibiscus moscheutos* L. 'Luna Blush' (hibiscus).

Materials and Methods

Substrate chemical properties. Samples of VC and pine bark were collected and submitted to the NC Department of Agriculture and Consumer Services (NCDA&CS), Agronomic Division, Raleigh for total nutrient analysis, cation exchange capacity, electrical conductivity (EC), and pH (Table 1). Before analysis, samples were dried at 65 °C and ground with a stainless steel grinder (ED-5 Wiley Mill; Thomas Scientific, Swedesboro, NJ) through a 1-mm screen (Campbell and Plank, 1992). Total carbon and N concentrations were determined by oxygen combustion gas chromatography with an elemental analyzer (NA 1500; CE Elantech Instruments, Lakewood, NJ) (Campbell, 1992). Total P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and sodium (Na) concentrations were determined with an inductively coupled plasma (ICP) spectrometer (Donohue and Aho, 1992) (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Shelton, CT) after open-vessel HNO₃ digestion in a microwave digestion system (CEM Corp., Matthews, NC) (Campbell and Plank, 1992). EC was determined using a 1:2 (v/v) substrate to distilled water extract, and pH was determined using a 1:1 (v/v) substrate to distilled water slurry. Cation exchange capacity was determined by summation of basic cations (excluding Na) and buffer acidity (Mehlich et al., 1976).

Experimental design and substrates. The study was a randomized complete block design with four treatments, four blocks, and seven plants (experimental units) per plot. Substrates included milled pine bark (less than 1.25 cm, aged 1 year) amended with 20% VC (by vol.) (NatureWorks Organics, Advance, NC) derived from pig manure (hereafter referred to as 20VC) and pine bark amended with 11% sand (by vol.), 1.8 kg·m⁻³ dolomitic limestone, and 0.9 kg·m⁻³ Micro-max® (Scotts, Marysville, OH) (hereafter referred to as PBS). Substrates were blended with a 0.76-m⁻³ rotary mixer (Bouldin & Lawson, LLC, McMinnville, TN). The 20VC substrate had an equivalent VC loading rate a 270 mg VC/3.8-L container (dry mass basis).

Fertilizers and nutrients. The CRFs formulated by Harrell's Fertilizer Inc. (Lakeland, FL) were 17N–2.4P–10K (17–6–12, 3–

4 month, 12.3% urea, 3.4% nitrate, 1.3% ammonia), 17N–0P–10K (17–0–10, 3–4 month, 13.6% urea and 3.4% nitrate), and 17N–0P–0K (17–0–0, 3–4 month, 17% urea). Fertilizers were applied as a topdressing at a rate of 5 g N/3.8 L (29.4 g fertilizer per container). To ensure N was not limiting, the rate of applied N was higher than the CRF incorporation rate of 0.75 to 0.9 kg N/m³ (2.8–3.4 mg N/3.5-L container) recommended by Pilon (2006). For one plant per plot, CRF was divided into two half-ellipse-shaped bags (15.9 cm × 5.8 cm) made from mosquito mesh (No-See-Um Mosquito Net; REI, Sumner, WA; Catalog Number 601044) and placed on the substrate surface (to simulate topdressing) for quantification of nutrients remaining in the CRF at the study termination.

The cumulative available N [N(20%)_{rel}] provided by 20% VC substrates after 8 weeks was estimated at 305 mg N/3.8-L container as determined by the following first-order nutrient release model developed from a laboratory mineralization study using vermicomposted pig manure McGinnis (2010): $N(20\%)_{rel} = a(1 - e^{-kt})$, where $a = 9.8\%$ (the potentially available N percentage of the total N loading rate), $k = 0.13$ week⁻¹ (the first-order rate constant), and $t = 8$ weeks. The initial total N loading rate from the VC was 4868 mg/3.8 L. Based on the nutrient release model, the total estimated available N was 477 mg N, and the estimated available N released at Week 8 was 305 mg N.

The available P provided by 20% VC substrates was estimated at 1721 mg P per 3.8-L container based on the NCDA&CS Plant/Waste/Solution Analysis Section P availability coefficient of 0.75 for composted swine waste (Brenda R. Cleveland, Chief, Plant/Waste/Solution Analysis Section, Agronomic Division, NCDA&CS, Raleigh, personal communication). The initial total P loading rate from the VC was 4590 mg/3.8 L. Assuming P will be available in one growing season (16 weeks), the plant-available P at Week 16 was calculated to be 3442 mg/3.8 L. McGinnis

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Table 1. Initial nutrient concentrations of substrate components.

Measure	Vermicompost ^z	Pine bark ^z
Nitrogen (mg·g ⁻¹)	18 ± 2	4.1 ± 0.04
Phosphorus (mg·g ⁻¹)	17 ± 2	0.4 ± 0.07
Potassium (mg·g ⁻¹)	1.5 ± 0.2	0.9 ± 0.15
Calcium (mg·g ⁻¹)	55 ± 7	4.6 ± 0.01
Magnesium (mg·g ⁻¹)	2.3 ± 0.3	0.7 ± 0.01
Sulfur (mg·g ⁻¹)	3.5 ± 0.5	0.4 ± 0.03
Iron (μg·g ⁻¹)	4,333 ± 565	3,002 ± 162
Manganese (μg·g ⁻¹)	480 ± 45	143 ± 4
Zinc (μg·g ⁻¹)	550 ± 64	39 ± 2
Copper (μg·g ⁻¹)	112 ± 11	12 ± 4
Boron (μg·g ⁻¹)	0.2 ± 0.2	2 ± 0
Sodium (μg·g ⁻¹)	571 ± 70	286 ± 30
Carbon:nitrogen	8.4 ± 0.01	120 ± 3
pH	5.6 ± 0.0	4.1 ± 0.0
EC ^y (dS·m ⁻¹)	5.5 ± 0.3	0.4 ± 0.06
CEC ^x (meq/100 cm ³)	61.1 ± 3.1	—

^zMeans ± 1 SE based on three observations.

^yEC = electrical conductivity.

^xCEC = cation exchange capacity.

(2010) and Nair et al. (2003) reported a zero-order (linear) nutrient release model of P from compost; therefore, the plant-available P estimated to be released at Week 8 was 1721 mg P, 50% of that estimated to be released at Week 16. It should be noted that "There is no universally accepted method to determine plant available phosphorus in compost" (Thompson, 2003).

Treatments, plant material, and irrigation. The four treatments yielded from the substrates and fertilizer combinations were: 20VC + NPK (20% VC and 17–6–12), 20VC + NK (20% VC and 17–0–10), 20VC + N (20% VC and 17–0–0), and PBS + NPK (PBS and 17–6–12). Treatment PBS + NPK served as an industry standard (or control) receiving conventional nursery crop nutrient inputs. Conventional nutrients include dolomitic limestone (to provide liming adjustment, Ca, and Mg), sulfated micronutrients (to provide S, Fe, Mn, Zn, Cu, and B), and CRF containing NPK as recommended by the best management practices guide for producing nursery crops (Yeager et al., 2007).

On 22 May 2006, seed-propagated *Hibiscus moscheutos* L. 'Luna Blush' (hibiscus) transplants obtained from Ball Seed Co. (Chicago, IL) were potted into 3.8-L black containers, placed on 16 separate plots at the Horticulture Field Laboratory at NC State Univ., Raleigh, and topdressed with CRF. Each gravel-covered plot (8 × 1 m) was underlain with corrugated plastic at a 2% slope, which directed all leachate from each plot to a 19-L collection vessel. Hibiscus is a hardy perennial (USDA hardiness zone 4–9) native to the southeastern United States. The compact, branched, shrubby growth habit lends itself to production in 3.8-L containers. The 6-inch to 8-inch flowers, which open in the morning and senesce each evening, start to show color as early as 7 weeks after transplant (Pilon, 2006). When flowering, hibiscus offers excellent color impact at the point of sale.

Irrigation was applied through pressure-compensated spray stakes (Acu-Spray Stick; Wade Mfg. Co., Fresno, CA; 200 mL·min⁻¹) with the daily total volume divided into three cycles (1200, 1500, and 1600 hr). Volumes of irrigation water applied (influent) and leached (effluent) for each plot were measured daily (volumetrically), and leaching fraction (LF) was calculated according to the following equation: LF = volume leached ÷ volume applied. Influent volumes were measured as the volume collected in a 4-L vessel from a spray stake on each plot, and effluent volumes were determined by the volume collected in a 19-L leachate vessel at each plot. Influent volumes were adjusted daily to maintain the LF for each plot. Data were compiled to determine cumulative influent per 3.8-L container and cumulative effluent per 3.8-L container. Cumulative volume water retained per 3.8-L container was calculated as the sum of the daily difference between influent and effluent volumes per container. Water use ratio (WUR) was calculated according to the following equation:

$WUR (mL \cdot g^{-1}) = \text{cumulative volume water retained by per 3.8-L container at day of harvest} \div \text{total plant dry mass}$. Effluent volumes were measured after rain events with less than 0.64 cm of rain; however, data collected on these days were not used in the cumulative influent and effluent calculations. Rain events with greater than 0.64 cm of rain resulted in overflow of the 19-L leachate vessels; thus, the exact volume was not known and analysis of the leachate would not provide useful information because content could not be calculated. A total of 31.8 cm of rain fell on 17 separate days during the study resulting in 8 d of data not included in cumulated totals.

Plant growth and nutrient content. On 23 June 2006 [35 d after potting (DAP)] and 18 July 2006 (56 DAP), one and two plants, respectively, per plot of hibiscus were harvested and partitioned into roots, stems, leaves, and flower buds. Substrate was removed from roots using a high-pressure water stream, and plants were dried at 65 °C to a constant weight (5 d) before obtaining dry weights of all segregated parts. On flowering, dates and number of open flowers were recorded for each plant and removed on senescence (within 24 h). Total plant dry weight was calculated according to the following equation: total dry weight (g) = root dry weight + stem dry weight + leaf dry weight + flower bud dry weight.

All tissues were ground separately using a Foss Tecator Cyclotec™ 1093 sample mill (Cyclotec; Analytical Instruments, LLC, Golden Valley, MN) to pass a 0.5-mm sieve or smaller. Stem and roots were ground initially with a Model 4 bench, IHP Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass through a 6.0-mm sieve or smaller before passing through the Cyclotec. Tissue samples were analyzed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and B concentrations by the NCDA&CS, Agronomic Division, by methods described previously. Total nutrient content was determined by multiplying dry weight by nutrient concentration.

Effluent nutrient contents, nutrient budgets, and nutrient use efficiencies (nitrogen and phosphorus). A nutrient budget was developed for each treatment to quantify the water-soluble fate of N and P added as CRF and VC. Recovered nutrient (RN) for N (RN_N) and P (RN_P) was calculated as follows: RN = nutrient in plant + cumulative nutrient lost with effluent + water-soluble nutrient remaining in substrate + nutrient remaining in CRF. The nutrient use efficiency (NUE) for N (NUE_N) and P (NUE_P) are as follows: $NUE = \{\text{plant absorbed nutrient} \div [(\text{added nutrient by CRF and VC}) + (\text{nutrient remaining in CRF} + \text{water-soluble nutrient remaining in substrate})]\} \times 100$.

Total N and P in plant tissue were determined by NCDA&CS as described previously. Nitrogen in the effluent, substrate, and CRF were quantified as N partitioned as water-soluble ammonium (NH₄-N) and nitrate (NO₃-N) and P was quantified as dissolved reactive P (DRP). Inorganic N (IN-N)

was calculated as the sum of NH₄-N and NO₃-N. Water-soluble nutrients remaining in the substrate (released from VC or CRF) at 56 DAP were measured on the extract from a 1:3 (v/v) substrate to deionized water slurry that was shaken for 1 h and filtered through a Whatman #2 filter (Whatman, Inc., Florham Park, NJ). Nutrients remaining in the CRF were determined by blending CRF prills remaining in the nylon mesh bags at 56 DAP with deionized water for 1 min and filtering through a Whatman #2 filter. The effluent, substrate extract, and CRF solution samples were analyzed colorimetrically using a continuous Flow Injection Analyzer (QuikChem 8500 System; Lachat Instruments-A Hach Company Brand, Loveland, CO) to quantify NH₄-N, NO₃-N, and DRP.

Statistical analysis. All variables were analyzed using Proc analysis of variance in SAS Version 9.01 (SAS Inst. Inc., Cary, NC). Treatment comparisons were made by Fisher protected least significant difference ($P = 0.05$).

Results and Discussion

Plant growth. At 35 and 56 DAP, stem and leaf dry weights were similar for all three 20VC treatments, and stem and leaf dry weights of all 20VC treatments were greater than PBS + NPK (Table 2). Flower bud dry weight and number were similar for all four treatments at 35 DAP. At 56 DAP, flower bud dry weight and number were similar for all three 20VC treatments, and flower bud dry weight and number of all 20VC treatments were greater than PBS + NPK. Root dry weights of hibiscus grown in 20VC + NPK and 20VC + NK were greater than 20VC + N and PBS + NPK at DAP 35 and greater than 20VC + N at 56 DAP. 20VC + N without K resulted in less root growth compared with 20VC treatments with K applied, yet root growth was similar to PBS + NPK. The lower root growth of 20VC + N was offset by greater leaf growth, resulting in similar total dry weights of all three 20VC treatments, which were all greater than PBS + NPK at 56 DAP. No nutrient deficiency visual symptoms were observed on any treatment on either harvest date. Plants grown in all treatments were flowering and judged to be saleable at 56 DAP.

Increased top (shoot and stem) dry weight, root dry weight, and/or flower production of containerized crops grown in ≈20% VC substrates has been reported by others (Arancon et al., 2008; Atiyeh et al., 2002; Bachman and Metzger, 2008; Hidalgo and Harkness, 2002; McGinnis, 2007). However, in contrast to experimental treatments here, complete fertilizers were provided. Thus, the benefit of increased growth for plants produced in substrates amended with this source of VC can be realized even when all fertilizer nutrient inputs except N are eliminated. The reduction of conventional nutrient inputs and the use of "recycled" nutrients from the VC may be of interest to some growers.

Table 2. Effect of nutrient inputs on dry tissue weights, flower number, and water use ratio (WUR) of *Hibiscus moscheutos* 'Luna Blush' at 35 and 56 d after potting (DAP).

DAP	Substrate ^z	Root dry wt	Stem dry wt	Leaf dry wt	Flower bud dry wt	Total dry weight	Flower number ^y	WUR ^x (mL·g ⁻¹)
		(g)						
35	20VC + NPK	4.0 a ^{wv}	2.7 a	7.4 a	0.15 a	14.2 a	15.3 a	839 b
	20VC + NK	3.8 a	2.5 a	7.1 a	0.10 a	13.6 a	14.0 a	898 b
	20VC + N	2.5 b	2.2 a	6.5 a	0.09 a	11.3 b	9.3 a	945 b
	PBS + NPK	2.3 b	1.5 b	4.3 b	0.10 a	8.2 c	5.5 a	1,525 a
56	20VC + NPK	17.0 a	12.6 a	18.4 a	5.02 a	53.1 a	54.5 a	659 a
	20VC + NK	16.3 ab	12.6 a	18.1 a	5.55 a	52.5 a	54.6 a	678 a
	20VC + N	13.3 c	12.7 a	19.6 a	4.41 a	50.1 a	58.4 a	639 a
	PBS + NPK	13.6 bc	8.8 b	13.3 b	1.49 b	37.2 b	28.9 b	818 a

^zPBS = 8 pine bark:1 sand with 1.8 kg·m⁻³ dolomitic limestone and 0.9 kg·m⁻³ Micromax[®] (Scotts, Marysville, OH); 20VC = 20% vermicompost-amended pine bark (by volume); NPK = 17N-2.4P-10K; NK = 17N-0P-10K; N = 17N-0P-0K.

^yFlower number = number of senesced flowers removed before harvest.

^xWUR (water use ratio) = volume of water retained by substrate (mL) ÷ total plant dry weight (g).

^wEach mean is based on four observations.

^vMeans within each variable (column) and DAP followed by the same letter are not significantly different as determined by Fisher's protected least significant difference at $P \leq 0.05$.

Irrigation measures. The LF averaged 0.24, 0.23, 0.25, and 0.25 for 20VC + NPK, 20VC + NK, 20VC + N, and PBS + NPK, respectively. No differences between treatments were detected at either 35 or 56 DAP for cumulative influent per 3.8-L container (mean = 16.2 L ± 0.1 for 35 DAP; mean = 42.6 L ± 1.0 for 56 DAP), cumulative effluent per 3.8-L container (mean = 4.5 L ± 0.2 for 35 DAP; 9.9 L ± 0.8 for 56 DAP), or cumulative water retained per 3.8-L container (mean = 11.8 L ± 0.5 for 35 DAP; 32.7 L ± 0.8 for 56 DAP) (data not presented). At 35 DAP, WUR was similar for 20VC treatments, and all were improved compared with the PBS treatment. At 56 DAP, WUR was similar for all treatments (Table 2).

The greater plant growth of the 20VC treatments compared with PBS treatment at 35 DAP in conjunction with similar cumulative water retained per 3.8-L container volumes for all treatments resulted in a

statistically significant improvement of use of water resources (i.e., improved WUR) (Table 2). Although statistical WUR differences were not detected at 56 DAP, similar irrigation volumes were applied to all treatments, yet the 20VC treatments had greater growth occurred compared with the PBS treatment (Table 2). If production time was shortened as a result of increased growth of plants grown in 20VC substrates, it would follow to reason that less irrigation volume would be used.

Plant tissue nutrient content. Root, stem, leaf, flower bud, and total plant content of P, Ca, Mg, S, Fe, Mn, Zn, Cu, and B grown in the 20VC treatments were equivalent to or greater than PBS + NPK (Table 3). These results indicate this source of VC supplied these nutrients in equivalent or greater amounts than conventional fertilizer inputs. However, total plant K content of 20VC + N was less than 20VC + NPK, 20VC + NK, and

PBS + NPK (Table 3). This indicates 20VC did not supply plant-available K at quantities equivalent to that supplied by conventional fertilizer inputs. Total plant N content of PBS + NPK was less than 20VC + NPK and 20VC + N and equivalent to that of 20VC + NK. Total N content of 20VC + N was greater than that of 20VC + NPK (Table 3). These results suggest that the additional N associated with the VC is not responsible (at least directly) for the increased plant growth associated with the 20VC treatments nor was N growth-limiting for the PBS + NPK treatment.

Total plant nutrient uptake was similar for all three 20VC treatments with the following exceptions: K, Ca, and Mg. Total plant K content of 20VC + N was less than 20VC + NPK and 20VC + NK; however, total plant Ca and Mg of 20VC + N was greater than the other two 20VC treatments. Similar trends were observed with root, stem, leaf, and flower bud K content, stem and leaf Ca

Table 3. Effect of nutrient inputs on macronutrient content of *Hibiscus moscheutos* 'Luna Blush' tissues at 56 d after potting.

Tissue	Substrate ^z	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur	Iron	Manganese	Zinc	Copper	Boron
		(mg)						(μg)				
Root	20VC + NPK	121 a ^{yx}	64 a	199 a	101 a	56 a	26 a	1,605 a	802 b	1,670 b	230 b	242 a
	20VC + NK	96 a	58 ab	200 a	98 a	53 a	25 a	1,556 a	713 b	1,669 b	208 b	244 a
	20VC + N	126 a	49 b	44 b	91 a	50 a	24 a	1,360 a	727 b	1,959 a	197 b	201 a
	PBS + NPK	99 a ^x	16 c	181 a	57 b	54 a	20 a	1,794 a ^y	1,174 a	1,210 c	308 a	215 a
Stem	20VC + NPK	76 b ^x	35 a	159 ab	165 b	30 b	11 b	464 a	571 b	576 a	114 a	218 a
	20VC + NK	61 b	33 a	172 a	159 b	26 b	11 b	538 a	566 b	528 a	102 a	232 a
	20VC + N	108 a	36 a	40 c	211 a	56 a	13 a	471 a	672 b	595 a	119 a	230 a
	PBS + NPK	64 b	9 b	141 b	61 c	25 b	7 c	347 b	868 a	404 b	96 b	168 b
Leaf	20VC + NPK	332 b	69 b	244 b	540 b	93 b	31 a	3,933 a	4,493 a	1,996 a	162 a	555 a
	20VC + NK	291 bc	69 b	257 b	526 b	86 b	32 a	6,448 a	4,372 a	1,867 a	168 a	542 a
	20VC + N	417 a	86 a	68 c	722 a	148 a	35 a	1,404 a	5,525 a	1,783 a	157 a	571 a
	PBS + NPK	257 c	16 c	338 a	215 c	78 b	24 b	2,945 a	5,371 a	1,702 a	127 a	481 a
Flower bud	20VC + NPK	174 a	29 a	138 a	114 a	30 a	12 a	328 ab	864 a	357 a	111 a	157 a
	20VC + NK	176 a	30 a	149 a	122 a	32 a	13 a	403 a	850 a	399 a	126 a	178 a
	20VC + N	155 a	24 a	59 b	108 a	25 a	11 a	250 bc	753 a	271 a	97 a	147 a
	PBS + NPK	40 b	3 b	32 b	18 b	8 b	3 b	155 c	351 a	89 a	47 b	38 b
Total	20VC + NPK	630 ab	184 a	680 a	870 b	195 b	75 a	6,189 a	6,354 a	4,445 a	569 a	1,106 a
	20VC + NK	581 bc	182 a	741 a	874 b	189 b	78 a	8,844 a	6,289 a	4,363 a	572 a	1,151 a
	20VC + N	768 a	190 a	196 b	1,105 a	272 a	80 a	3,422 a	7,489 a	4,540 a	546 a	1,112 a
	PBS + NPK	436 c	43 b	673 a	341 c	160 c	51 b	5,148 a	7,553 a	3,352 b	550 a	879 b

^zPBS = 8 pine bark:1 sand with 1.8 kg·m⁻³ dolomitic limestone and 0.9 kg·m⁻³ Micromax[®] (Scotts, Marysville, OH); 20VC = 20% vermicompost-amended pine bark (by volume); NPK = 17N-2.4P-10K; NK = 17N-0P-10K; N = 17N-0P-0K.

^yEach mean is based on four observations.

^xMeans within each variable (nutrient) and plant tissue type followed by the same letter are not significantly different as determined by Fisher's protected least significant difference at $P \leq 0.05$.

content, and stem and leaf Mg content. The increased Ca and Mg total content of 20VC + N may be a result of reduced competitive uptake inhibition by K (Mill and Jones, 1991). Some physiological roles of K can be replaced by other cations, which may explain why no decreased plant growth was associated with 20VC + N treatments (Wyn-Jones et al., 1979).

Effluent nutrient contents, nutrient budgets, and nutrient use efficiencies (nitrogen and phosphorus). At 56 DAP, the IN-N and DRP effluent content of the 20VC treatments were similar, and the IN-N and DRP effluent contents of the 20VC treatments were greater than PBS + NPK (Tables 4 and 5). The

average IN-N effluent content of the 20VC treatments (243 mg) was 186 mg greater than the effluent content of PBS + NPK (47 mg) (Table 4), and the average DRP effluent content of the 20VC treatments (415 mg) was 408 mg greater than the effluent content of PBS + NPK (7 mg). The 20VC treatment IN-N effluent content average of 126 mg at 5 DAP and DRP effluent content average of 208 mg at 10 DAP amounted to 50% of the effluent content at 56 DAP (data not presented).

The contents of N recovered (RN_N) for all 20VC treatments were similar, and RN_N content of all 20VC treatments was greater than PBS + NPK. Interestingly, the RN_N

content average of the VC treatments (1051 mg) was 352 mg greater than PBS + NPK (699 mg), which is similar to the estimated N input provided by VC (305 mg). This suggests the estimated available N provided by VC was on target. The recovered N as a percent of total N inputs (RN_N%) and N use efficiency (NUE_N) of all 20VC treatments was greater than PBS + NPK (Table 4).

The contents of P recovered (RN_P) for all 20VC treatments were greater than PBS + NPK (Table 5). The RN_P content ranged from 560 to 650 mg greater than that recovered from PBS + NPK (100 mg). This difference is 33% to 38% of that estimated P from VC. This may indicate that the available P content provided by VC was overestimated. Predicting the availability of P is difficult, because P release from compost is governed by complex interactions of chemical and physical conditions. An overestimate of P is conservative with respect to determining efficiency measures. Regardless, this source of VC provided sufficient P such that additional P inputs from fertilizer or other sources are not necessary. Both the percent of P input that was recovered (RN_P%) and the phosphorus use efficiency (NUE_P) would be underestimated if the P input is overestimated. The RN_P% and NUE_P of the 20VC treatments were greater than the PBS + NPK (Table 5).

For 20VC + NPK, 20VC + NK, 20VC + N, and PBS + NPK, the NUE_N was 12%, 11%, 15%, and 9% and NUE_P was 8%, 11%, 12%, and 7%, respectively (Tables 4 and 5). These nutrient use efficiency values are at the lower end of the ranges reported by others (Owen et al., 2008; Ristvey et al., 2007; Stoven et al., 2006). For azalea (*Rhododendron* var. L. 'Karen') grown in 2002 fertilizer treatments in which decreased growth was not detected, the NUE_N and NUE_P ranged from 12% to 28% and 14% to 49%, respectively (Ristvey et al., 2007). These higher nutrient use efficiencies were associated with lower respective N and P fertilization rates. Owen et al. (2008) also reported an increased NUE_P from 21% to 34% when cotoneaster (*Cotoneaster dammeri* Schnied. 'Skogholm') grown in a pine bark sand substrate received P at a full rate and half rate, respectively. Specific crop nutrient requirements will also influence nutrient use efficiencies. Stoven et al. (2006) reported NUE_N of 6%, 14%, 36%, and 55% for *Quercus rubra* L. (red oak), *Malus* (Mill.) 'Prairifire' (Prairifire crabapple), *Cercis canadensis* L. (Eastern redbud), and *Acer xfreemai* 'Jeffersred' (Autumn Blaze® maple), respectively, when grown outdoors and fertilized with CRF. Reduction of LF is another approach to improve nutrient use efficiency (Fare et al., 1994; McGinnis, 2007; Owen et al., 2008; Tyler et al., 1996). Leaching fraction reduction results in decreased nutrient effluent volume and content. Consequently, the nutrients not lost with the effluent remain in the container and can be absorbed by the plant, resulting in greater nutrient use efficiency.

In conclusion, nutrient uptake of P, Ca, Mg, S, Fe, Mn, Zn, Cu, and B was equivalent

Table 4. Nitrogen partition of *Hibiscus moscheutos* 'Luna Blush' grown with different nutrient inputs at 56 d after potting.

Nitrogen partition	20VC + NPK ^z	20VC + NK ^z	20VC + N ^z	PBS + NPK ^z
Inputs				
Fertilizer (mg)	5,000 ^y	5,000	5,000	5,000
Vermicompost (mg)	305 ^y	305	305	0
Outputs				
Effluent NO ₃ -N (mg)	233 a ^{yx}	227 a	222 a	48 b
Effluent NH ₄ -N (mg)	15 a ^{yx}	14 ab	17 a	9 b
Hibiscus (mg)	630 ab ^{yx}	581 bc	768 a	436 c
Remaining in system				
Substrate NO ₃ -N (mg)	12.6 ab ^{yx}	29.1 ab	6.0 b	40.3 a
Substrate NH ₄ -N (mg)	11.7 b ^{yx}	22.9 ab	49.3 a	9.6 b
Fertilizer NO ₃ -N (mg)	126.0 b ^{yx}	147.8 a	0.2 c	122.3 b
Fertilizer NH ₄ -N (mg)	36.9 a ^{yx}	1.3 b	1.7 b	34.1 a
Recovered nutrient (RN _N) ^w (mg)	1,065 a ^{yx}	1,022 a	1,064 a	699 b
Recovered nutrient (RN _N) ^v (%)	20 a ^{yx}	19 a	20 a	14 b
Nutrient use efficiency (NUE _N) ^u (%)	12 ab ^{yx}	11 bc	15 a	9 c

^zPBS = 8 pine bark:1 sand with 1.8 kg·m⁻³ dolomitic limestone and 0.9 kg·m⁻³ Micromax® (Scotts, Marysville, OH); 20VC = 20% vermicompost-amended pine bark (by volume); NPK = 17N-2.4P-10K; NK = 17N-0P-10K; N = 17N-0P-0K.

^yEach mean is based on four observations.

^xMeans within each variable (row) followed by the same letter are not significantly different as determined by Fisher's protected least significant difference at $P \leq 0.05$.

^wRN_N (mg) = N in plant + effluent + substrate + fertilizer prills.

^vRN_N (%) = (N in plant + effluent + substrate + fertilizer prills) ÷ N inputs * 100.

^uNUE_N = {plant absorbed nutrient (mg) ÷ [applied nutrient (mg) - nutrient remaining in CRF prill - nutrient remaining in substrate]} * 100.

Table 5. Phosphorus partition of *Hibiscus moscheutos* 'Luna Blush' grown with different nutrient inputs at 56 d after potting.

Phosphorus partition	20VC + NPK ^z	20VC + NK ^z	20VC + N ^z	PBS + NPK ^z
Inputs				
Fertilizer (mg)	706 ^{yx}	0	0	706
Vermicompost (mg)	1,721 ^{yx}	172	1,721	0
Outputs				
Effluent (mg)	430 a ^{yx}	395 a	421 a	7 b
Hibiscus (mg)	184 a ^{yx}	182 a	190 a	43 b
Remaining in system				
Substrate (mg)	83.0 a ^{yx}	96.7 a	104.5 a	4.2 b
Fertilizer prills (mg)	58.8 a ^{yx}	0 b	0.1 b	55.3 a
Recovered nutrient (RN _P) ^w (mg)	756 a ^{yx}	674 b	716 ab	110 c
Recovered nutrient (RN _P) ^v (%)	31 b ^{yx}	39 a	42 a	16 c
Nutrient use efficiency (NUE _P) ^u (%)	8 b ^{yx}	11 a	12 a	7 c

^zPBS = 8 pine bark:1 sand with 1.8 kg·m⁻³ dolomitic limestone and 0.9 kg·m⁻³ Micromax® (Scotts, Marysville, OH); 20VC = 20% vermicompost-amended pine bark (by vol.); NPK = 17N-2.4P-10K; NK = 17N-0P-10K; N = 17N-0P-0K.

^yEach mean is based on four observations.

^xMeans within each variable (row) followed by the same letter are not significantly different as determined by Fisher's protected least significant difference at $P \leq 0.05$.

^wRN_P (mg) = N in plant + effluent + substrate + fertilizer prills.

^vRN_P (%) = (N in plant + effluent + substrate + fertilizer prills) ÷ N inputs * 100.

^uNUE_P = {plant absorbed nutrient (mg) ÷ [applied nutrient (mg) - nutrient remaining in CRF prill - nutrient remaining in substrate]} * 100.

or greater by hibiscus-grown pine bark amended with this source of vermicomposted pig manure (20% by vol.) compared with plants grown with conventional nutrient conventional nursery crop nutrient inputs (dolomitic limestone, sulfated micronutrients, and P in the CRF). This source of VC did not supply equivalent K as conventional CRFs. Although the lower K uptake did not reduce plant growth, the addition of fertilizer K is recommended to fertilizer. K should be provided to this source of VC at a 20% amendment rate. Furthermore, hibiscus grown in all 20% VC treatments produced 40% greater plant dry weight and 93% more flowers compared with hibiscus grown in the industry standard treatment, yet all treatments used equivalent volumes of water. The effluent volumes for all treatments were also equivalent; however, the effluent content of IN-N and DRP was much greater for VC treatments. The drawback of greater effluent nutrient content when using a VC amended substrate could be offset by implementing best management practices such as the reduction of LF and/or containment or capture of the effluent.

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