ABSTRACT

MCGINNIS, MICHELLE S. Vermicompost Amended Pine Bark Substrate Improves Nursery Crop Production. (Under the direction of Stuart L. Warren and Ted E. Bilderback.)

Several field, greenhouse, and laboratory studies were conducted to evaluate the effects of vermicomposted (VC) hog manure amended to pine bark (PB) on substrate physical properties, plant growth and flower production, water use efficiency of productivity (WUE_P), effluent nitrogen and phosphorus content, substrate solution pH, macronutrient release rate characteristics, and the ability of VC to replace conventional fertilizer nutrient inputs. Nitrogen and phosphorus budgets were determined, and nutrient use efficiencies of nitrogen (NUE_N) and phosphorus (NUE_P) were calculated. Container capacity and available water increased linearly and air space decreased linearly with increasing rate of VC. Growth of several species increased linearly with increasing VC rate with no traditional amendments of limestone and micronutrients; and 20% VC resulted in greater plant dry weights than the PB control (amended with limestone and micronutrients). However, there were species where growth decreased linearly with increased VC rate, while the 20% VC maintained equivalent dry weights to the PB control. The WUE_P of several species were improved compared to the control. Liming effects of 5% VC were equivalent to the control receiving limestone, whereas VC rates >10% had greater liming effects compared to the respective control. Twenty percent VC provided sufficient quantities of P, Ca, Mg, S, and micronutrients such that an additional supply of these nutrients need not be applied. Although 20% VC did not supply K in quantities comparable to traditional inputs, the reduction of K did not affect growth or flower bud production of hibiscus. Macronutrient release rates (determined on a volume basis) of N and S from VC followed a first-order model, Ca and Mg followed a two

pool first/zero-order model, and P followed a zero-order model. The tissue nutrient content of N, Ca, Mg, and S increased with increasing VC rate while P decreased with decreasing VC rate. Vermicompost in the substrate increased N and P effluent content, but reducing the leaching fraction decreased nutrient contents. The NUE_N ranged from 9% to 20% with no major differences between substrate or leaching fraction treatments. However, the NUE_P was improved when VC was amended to the substrate.

Vermicompost Amended Pine Bark Substrate Improves Nursery Crop Production

by
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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Horticultural Science

Raleigh, North Carolina

2007

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DEDICATION

This work is dedicated to all the hard working

earthworms of the world.

BIOGRAPHY

Michelle was raised in Chambersburg, Pennsylvania. She graduated from Indiana University of Pennsylvania in 1992 with a B.S. in Environmental Health / Minor in Biology and from University of North Carolina at Chapel Hill in 1994 with a M.S.P.H. in Environmental Sciences and Engineering. She worked as an environmental consultant and ornamental plant grower/maintenance technician for nine years before starting a doctoral program with the Nursery Crops Science group in the Department of Horticultural Science in 2003. While completing her dissertation, Michelle began working at the North Carolina Department of Agriculture & Consumer Services, Agronomic Division, Plant/Waste/Solution Analysis Section in Raleigh, North Carolina. Michelle lives in Chatham County with her husband, dog, and two cats.

ACKNOWLEDGEMENTS

I'd like to gratefully acknowledge and extend much appreciation to my advisors, Stu Warren and Ted Bilderback, for their constant and support, guidance, and mentorship. I feel lucky to have worked with two such wonderful people. I'd also like to thank my committee, Paul Nelson, Michael Wagger, and Helen Kraus for providing valuable insights and thought provoking discussions. I can't imagine working with a better group of people with complementing specialties, personalities, knowledge, insights, and experiences. Many thanks to William Reece and Mary Lorscheider. The technical training and guidance they provided was invaluable and critical to my education. William's good humor and deep insights into the world always put things into the proper perspective, and those lessons I will never forget. I extend my gratitude to the rest of the research family, the graduate and undergraduate students who have come and gone over the last four years. There are too many to mention, but their assistance, company, and friendship certainly made some grueling research tasks almost fun! Also, a special thanks to former fellow graduate student, Jim Owen, who unwittingly served as a mentor during my program. Also, thanks to friends and family, especially my sister, Kathy. I gratefully acknowledge the following for providing funding for my graduate program: EPA STAR Fellowship, Horticultural Science Teaching Assistantship, Monaco Horticultural Science Graduate Fellowship Endowment for Diversity, NatureWorks Organics, and my advisors. Lastly, thanks to Dmitri Hammer for his love, patience, voice of reason, appreciation of my humor, and simply being in my life.

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INTRODUCTION

My dissertation addressed environmental issues of two important agricultural commodities in North Carolina, the hog industry (#1 agricultural commodity) and greenhouse/nursery industry (#1crop commodity). I did this by investigating the use of a value-added material resulting from vermicomposted hog manure (vermicompost or worm castings) as a substrate amendment of nursery crops. Benefits to the environment include the cycling of nutrients through managed systems; benefits to the hog industry include the transformation of a waste product into a desirable and saleable product; and the benefits to the nursery industry are the focus of this research.

Environmental problems and surface water quality issues occurred with the rapid increase of swine production in eastern North Carolina in the 1990s, when the number of hogs increased from 2 million in 1992 to 10 million in 1998. Not surprisingly, the volume of hog waste exceeded the capacity of traditional treatment technologies (anaerobic lagoons and spray fields). Over application of waste to spray fields and failure of lagoons resulted in nutrient contamination of surface water and subsequent algae blooms and fish kills. There is currently a moratorium in place to prevent the further expansion of hog operations until alternative, effective, and affordable waste management technologies can be developed. A key component to any sustainable and successful treatment technology will include an environmentally sound and beneficial use for the treated product.

Vermicomposting is a hog waste management approach that has been shown to be economically and technologically feasible and yields desirable end products rich with humic substances and plant available nutrients (Albanell et al., 1988; Atiyeh et al, 2000a;

Hartenstein and Hartenstein, 1981) Vermicomposting uses earthworms (and bacteria) to reduce and stabilize hog waste in an aerobic, moist, non-thermophillic environment. Vermicomposting has been successfully used as a hog waste management method in North Carolina, and the value-added material produced, vermicompost, has been available commercially for over 12 years. Research results of studies conducted with greenhouse crops grown in soilless substrates amended with vermicompost have reported greater plant dry weight and flower production compared to controls (all treatments had conventional nutrient inputs as liquid fertilizer) (Atiyeh et al., 2000b; Atiyeh et al., 2001; Atiyeh et al., 2002; Hidalgo and Harkess, 2002a, 2002b). However, little research has been conducted to investigate if and how vermicompost will affect nursery crop production. Nursery crops differ from greenhouse crops in that they are generally perennial (herbaceous and woody) crops, grown in larger containers (≥ 3.8-L) outdoors in an uncontrolled environment in a high air filled porosity substrate (pine bark), and are fertilized with controlled release fertilizers.

A benefit vermicompost may provide to nursery crop production systems is the improvement of substrate physical properties, specifically to improve container capacity (water held against the pull of gravity) and available water (the percentage of container capacity held under a tension of 15 bar). Pine bark is the substrate of choice in the southeastern United States due to its availability, affordability, and desired physical properties (high air porosity). Substrates with high air filled porosity provide good drainage and prevent anoxic root conditions in times of heavy and/or frequent rainfall. However, because the substrates have good drainage, much water flows through a nursery. The "Best Management Practices: Guide for Producing Container-Grown Plants" (Yeager et al., 2007) is a compilation of science based research that can be implemented in the nursery to reduce water use. It encompasses proper irrigation system design, cyclic irrigation, container spacing, microirrigation, irrigation volumes to maintain a 0.2 leaching fraction (irrigation volume leached ÷ irrigation volume applied), and improved container capacity with amendments. These recommendations can assist growers to conserve irrigation water supplies and to reduce leaching of nutrients from the containers and out of the production areas.

Because soilless substrates such as peat moss and pine bark have low nutrient retention properties and little ability to provide nutrients to the substrate solution (i.e. low capacity or quantity factor), the nutrient concentrations in the substrate solution (i.e. intensity factor) is highly managed to provide nutrients to the plants. An additional benefit that vermicompost may provide to nursery crop production systems is the increase of capacity or quantity factor of the substrate. This would provide a source of some nutrients to recharge the substrate solution, and in the case of phosphorus, release into the solution would be partially driven by plant uptake, as phosphorus availability in mineral soil systems is driven by diffusion. The end result would be fertilizer nutrient inputs could be reduced and/or eliminated.

The objectives of this research were: (1) to determine the effect of increasing rates of vermicompost amended pine bark on substrate physical properties; (2) to identify a recommended vermicompost amendment rate based on plant growth and water use efficiency of productivity of several plant species (basil, cotoneaster, verbena, gardenia, coreopsis, and hibiscus); (3) to determine how irrigation volumes affect plant growth, water use efficiency of productivity, and nutrient effluent content in vermicompost amended pine bark; (4) to determine the macronutrient content and longevity supplied by vermicompost amended pine bark; and (5) determine if and which conventional nutrient fertilizer inputs can be reduced/eliminated with vermicompost amended to pine bark.

Literature Cited

Albanell, E., J. Plaixats, and T. Cabrero. 1988. Chemical changes during vermicomposting (*Eisenia foetida*) of sheep manure mixed with cotton industrial wastes. Biol. Fert. Soils. 6:266-269.

Atiyeh, R.M., N.Q. Arancon, C.A. Edwards, and J.D. Metzger. 2002. The influence of earthworm-processed pig manure on the growth and productivity of marigolds. Bioresource Technol. 81:103-108.

Atiyeh, R.M., J. Dominguez, S. Subler, and C.A. Edwards. 2000a. Changes in biochemical properties of cow manure during processing by earthworms (*Eisenia Andrei*) and the effects on seedling growth. Pedobiologia. 44:709-724.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2000b. Earthworm-processed organic wastes as components of horticultural potting media for growing marigold and vegetable seedlings. Compost Sci. Util. 8:215-223.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2001. Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physiochemical properties and plant growth. Bioresource Technol. 78:11-20.

Hartenstein, R., and F. Hartenstein. 1981. Physiochemical changes in activated sludge by earthworm *Eisenia foetida*. J. Environ. Quality. 10:377-382.

Hidalgo, P.R. and R.L. Harkess. 2002a. Earthworm castings as a substrate amendment for chrysanthemum production. HortScience 37:1035-1039.

Hidalgo, P.R. and R.L. Harkess. 2002b. Earthworm castings as a substrate amendment for poinsettia production. HortScience 37:304-308.

Yeager, T.H., C.H. Gilliam, T.E. Bilderback, D.C, Fare, A.X. Niemiera, K.M. Tilt, and S.W. Warren. 2007. Best Management Practices: Guide for Producing Container-Grown Plants. Southern Nursery Association, Marietta, GA.

Chapter 1

Vermicompost Amended Pine Bark Improves Substrate Physical Properties, Water Use Efficiency, and Growth of Genovese Basil

(In the format appropriate for submission to Compost Science and Utilization)

Vermicompost Amended Pine Bark Improves Substrate Physical Properties, Water Use Efficiency, and Growth of Genovese Basil

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Received for publication _____________. This research was funded in part by the North Carolina Agricultural Research Service (NCARS), Raleigh, NC 27695-7643 and the Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Fellowship. Use of trade names in this publication does not imply endorsement by the NCARS or EPA of products named nor criticism of similar ones not mentioned. Appreciation is extended to William M. Reece and Mary Lorscheider for technical assistance and William H. Swallow for statistical assistance. From a thesis submitted by M.S.M. in partial fulfillment of the requirements for the PhD degree.

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Subject Category: Soil Management, Fertilization, and Irrigation

Vermicompost Amended Pine Bark Improves Substrate Physical Properties, Water Use Efficiency, and Growth of Genovese Basil

Additional Index Words. Available water, container capacity, EC, hog manure, *Ocimum basilicum* 'Genovese' L., liming effects, pH, worm castings.

Abstract. Vermicompost (VC) is the end product of a waste management technology that may have value as a soilless substrate amendment for the production of containerized crops. The objectives of this study were to determine the effects of VC amended pine bark on substrate physical properties, water use efficiency of productivity (WUE_P), plant growth, and substrate solution pH. Two experiments were conducted to accomplish these objectives. The first study examined the effect of 0%, 5%, 10%, 20%, 40%, 60%, 80%, and 100% (v/v) VC amended pine bark on substrate physical properties. Total porosity (TP), container capacity (CC), available water (AW), and bulk density (D_b) increased linearly with increasing rate of VC; whereas air space (AS) decreased linearly with increasing VC rate. Increasing VC from 0% to 100% increased TP 7%, CC 26%, and AW 24%, and decreased AS 19%. Unavailable water (UW) followed a quadratic response with increasing VC rate with a calculated maximum UW at 54% VC. The percentage of fine particles ($\leq$ 0.5 mm) was best described by a decreasing linear plateau model with increasing VC rate (if VC < 52%, then $y = 13.7x^2 - 0.164x + 51.5$), with fine particles decreasing from 14% (by wt) at 0%

VC to a calculated plateau of 5.5% (by wt) at 52% VC. In the second study Genovese basil (*Ocimum basilicum* 'Genovese' L.) seedlings were grown for 5 weeks in pine bark amended with four rates of VC (0%, 5%, 10%, and 20% VC) and two controlled-released fertilizers (19N-2.2P-7.4K and 19N-2.2P-10.7K), which were chosen based on differences of N source. No limestone was added to pine bark amended with 5%, 10% or 20% VC, whereas the 0% VC (control) received 1.8 $kg \cdot m^{-3}$. Increasing VC rates increased substrate solution pH linearly. VC at 5% had equivalent liming effects as 1.8 $kg \cdot m^{-3}$ dolomitic limestone (control), whereas 10% and 20% VC had greater liming effects compared to the control. VC had no effect on substrate solution electrical conductivity (EC), however, CRF did affect EC. On 6 and 14 days after planting, substrate solutions from 19-5-9 had greater EC compared to 19-5-13 in all treatments. Otherwise, CRFs had minimal affect on all other measured variables. All plant part dry weights (root, stem, and leaf) increased linearly with increasing VC rate, and plants grown in 20% VC were significantly greater than the control. Top mineral nutrient tissue concentration of N, K, Mg, Fe, Cu, Zn, B, and Na were unaffected by VC rate, whereas top Ca and Mn concentrations increased and decreased, respectively, with increasing rate of VC. The WUE_p showed a linear decrease with increasing VC rate (less water was used to produce a gram of plant dry mass), and 20% VC was lower than the control. VC amended pine bark provided liming effects and pH buffering, improved physical properties, improved WUEp, and increased plant growth of all tissues. Increased plant growth does not appear to be due to nutrients supplied by VC, however improvements in physical properties may be responsible for increased growth and improved WUEp.

Introduction

High density livestock operations result in large quantities of nutrient rich waste that can exceed the volume capacity of traditional treatment/management methods (Mallin and Cahoon 2003). Nutrients in livestock waste can leach or runoff into surface waters and result in degraded water quality. As a result, alternative treatment methods have been recommended by scientists and sought or mandated by governmental agencies (Mallin and Cahoon 2003).

An alternative and sustainable approach for managing livestock waste is vermicomposting, a process by which earthworms and bacteria stabilize organic waste in an aerobic and non-thermophillic environment by cycling nutrients through biological systems. This process yields a value-added product, vermicompost (VC) or worm castings, which contains plant available nutrients and has excellent physical properties (aeration and water holding capacity) (Edwards 1995). VC is a proven technology that may be an economically feasible approach for managing animal waste and has been shown to eliminate pathogens to United States Environmental Protection Agency Class A stabilization (Eastman *et al*. 2001; Edwards 1995).

Horticultural crop container substrates may be a viable use of VC as the plant available nutrients can be used for crop production, thus continuing the cycling of nutrients concentrated in livestock waste through biological systems. Several studies have investigated benefits of VC amended peat moss based substrates and have reported increased plant growth of greenhouse crops, both with and without fertilizer added, as well as increased container capacity (CC) compared to non-amended controls (Atiyeh *et al*. 2000; Atiyeh *et al*.

2001; Atiyeh *et al*. 2002; Hidalgo and Harkess 2002). However, studies investigating VC amended pine bark, the primary nursery crop substrate in the southeastern U.S., are limited to the following three studies. Similar to results obtained with peat moss substrates, Bachman and Davis (2000) reported greater dry top and root weights of fertilized *Magnolia virginiana* seedlings grown in pine bark amended with 10% VC [derived from hog (*Sus sp.*) manure] compared to 0% VC. In a study where fertilizer was not applied, Hidalgo *et al*. (2006) reported greater growth of *Tagetes erecta* L. (African marigold 'Marvel Orange') in pine bark amended with VC [derived from cow (*Bos sp.*) manure] at 50% VC compared to 25% VC, most likely due to the greater quantity of plant available nutrients supplied by the higher VC rate. In contrast, Donald and Visser (1989) reported equivalent or decreased growth of three fertilized woody species (*Acacia mearnsii* De Wild., *Eucalyptus grandis* Hill ex Maid., and *Pinus patula* Schlechtend. & Cham.) grown in pine bark amended with increasing rates of VC derived from abattoir waste. However, the authors' noted the high initial K (1112 $mg \cdot kg^{-1}$) and Na (4800 $mg \cdot kg^{-1}$) of the VC most likely had deleterious affects on plant growth.

The effect of VC amended peat moss or pine bark on water use efficiency of productivity (WUE_p) (volume of water required to produce 1 gram of plant dry mass) has not been reported. Owen (2006) amended pine bark with an industrial aggregate clay which increased CC and AW which consequently improved water use efficiency of productivity (WUE_P). The result of improving CC and WUE_P benefits both growers and the environment by reducing irrigation volumes and providing more substrate water-buffering capacity which potentially reduce runoff. The objectives of this study were to determine the effects of VC amended pine bark on substrate physical properties, WUE_P, plant growth, and substrate solution pH.

Materials and Methods

Substrate physical properties

Substrate treatments included aged (~ 1 year) pine bark (≤ 12.7 mm) (Carolina Bark Products, Seaboard, N.C.) amended with VC derived from hog manure (Vermicycle Organics, Wilson, N.C.) at 0%, 5%, 10%, 20%, 40%, 60%, 80%, and 100% (v/v). The physical properties measured were total porosity (TP), air space (AS), CC, available water (AW), unavailable water (UW), bulk density (D_b), and particle size distribution. Physical property analyses were conducted at the Horticultural Substrates Laboratory, Department of Horticultural Science, N.C. State Univ., Raleigh.

Substrates were brought to a mass wetness of 276.7 $g \cdot g^{-1}$ ± 2.6. Four 347.5 cm^3 cylindrical aluminum rings (7.6 cm dia, 7.6 cm ht) and five 101.4 cm^3 cylindrical aluminum rings, (7.6 cm dia., 2.2 cm ht) of each substrate were packed using modified procedures of Bilderback et al. (1982). Three rings were stacked vertically and secured (with a base plate attached to the bottom ring), filled with a substrate, and tapped three times on a wooden surface from a consistent height (~5 cm). The upper and lower cylinders were removed and the center cylinder was retained for physical property analysis. All cylinders within each substrate treatment were packed to ± 2.2% wet D_b. The 347.5 cm^3 rings were used to determine TP, AS, CC, and D_b according to procedures outlined in Tyler *et al*. (1993). Unavailable water was determined using the 101.4 cm^3 rings following procedures described in Klute (1986), and AW was calculated as CC - UW. To determine particle size distribution, four samples of approximately 60 g of each substrate were dried at 105°C for 48 h and placed in a Ro-tap Shaker (Model B, W.S. Tyler, Mentor, Ohio) fitted with seven sieve plates for 5 min. The sample from each sieve plate was weighed, and particle size was expressed as a percentage of the total weight of the sample.

Basil production

Plant material, substrates, and fertilizers. Seeds of Genovese basil (*Ocimum basilicum* 'Genovese' L.) (Johnny's Selected Seeds, Winslow, ME) were sown in 96-cell flats on 24 Sept. 2003 containing Fafard 4P Mix Professional Formula (Agawam, Mass.). No additional fertilizer was added. The substrate treatments included pine bark amended with VC (as described previously) at 0%, 5%, 10%, or 20% VC (v/v). The 0% VC was amended with 1.8 $kg \cdot m^{-3}$ dolomitic limestone and served as the VC control. Two weeks after sowing, seedlings were transplanted into 10-cm dia. cylindrical containers (710 cm^3) filled with the substrate treatments.

Nutrient analysis of VC and the substrates were conducted by the N.C. Department of Agriculture (NCDA), Agronomic Division, Raleigh (Table 1). Prior to analysis, samples were dried for 5 days at 60°C and ground with a stainless steel grinder (ED-5 Wiley Mill; Thomas Scientific, Swedesboro, N.J.) to pass through a 20 mesh (1 mm) screen. Total carbon (C) and nitrogen (N) concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500, CE Elantech Instruments, Milan, Italy). Total phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) and sodium (Na) concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer, Perkin Elmer Corporation, Wellesley, Mass.), following open-vessel nitric acid (HNO_3) digestion in a microwave digestion system (CEM Corp., Matthews, NC). Electrical conductivity (EC) was determined using a 2 substrate : 1 distilled water extract, and pH was determined using a 1 substrate : 1 distilled water extract.

All substrate treatments were fertilized with one of two controlled-release fertilizers (CRF) with micronutrients (Harrell's, Lakeland, FL) which were chosen based on differences in N sources: 19N-2.2P-7.4K (19-5-9, 3-4 mo., 1.96% ammoniacal N, 10.04% urea N, and 7% water insoluble N, blended, nutrients had different coatings, P and K had no coating) and 19N-2.2P-10.7K (19-5-13, 3 mo., 8.21% ammoniacal N and 10.75% nitrate N, homogenous, all nutrients were in one prill). Both CRFs were topdressed at a rate of 0.88 g N per container and potted plants were placed in a glass greenhouse (day/night temperatures 24°C ±3°C /18°C ±2°C). Plants were grown for five weeks under natural irradiance and photoperiod.

Irrigation. Plants were watered by hand immediately after potting and hand watered several times over the course of the next 60 min. After draining for 60 min., each container was weighed to determine weight at CC. The pots were weighed daily and irrigation was applied when each container lost 50% to 60% AW. Upon loss of 50% to 60% AW, plastic saucers were placed beneath the containers, and water was hand applied according to the following calculation based on gravimetric measures to achieve a 0.2 leaching fraction described by Ku and Hershey (1992): $V = [(LF \times ET) \bullet (1 - LF)^{-1}] + ET$; where V = irrigation volume, LF = leaching fraction (volume leached ÷ volume applied), and ET = evapotranspiration (mass at CC – mass before irrigation). Thirty min. after water was applied, the leachate in the saucers was reapplied to the substrate surface. After another 30 min., the 0.2 LF was verified, and the leachate was discarded.

Substrate solution pH, EC, and nutrient concentrations. Substrate solution samples were collected weekly from four replications 60 min. following an irrigation event using the pour through nutrient extraction procedure (Wright, 1986). Substrate solution pH and electrical conductivity (EC) measurements were obtained using an Acument pH/conductivity benchtop meter (Fischer Scientific, Springfield, N.J.) and frozen immediately. Mineral nutrient analysis of substrate solution samples collected at 6 and 30 days after potting (DAP) was conducted by NCDA, Agronomic Division. Inorganic N (IN-N) was extracted from the VC using 0.1M H_2SO_4 ($1\ g \cdot 25\ ml^{-1}$) and partitioned into nitrate (NO_3) and ammonia (NH_4) fractions by EPA Methods 353.1 and 351.2, respectively, using an autoflow spectrophotometric analyzer (4001 San^{plus} Segmented Flow Analyzer; Skalar Instruments, Breda, The Netherlands). Total P and K concentrations were determined by methods described previously.

Plant growth, nutritional status, and water use efficiency. On 12 Nov. 2003 plants from all six replications were harvested and separated into roots, stems, and leaves. Leaf area was obtained on three replications using a LI-COR 3100C Area Meter (LI-COR Environmental, Lincoln, Nebr.). Plants were dried at 65°C to a constant weight prior to obtaining dry weights. From these data the following variables were calculated: top dry weight = leaf dry weight + stem dry weight, total dry weight = leaf dry weight + stem dry weight + root dry weight, root:top ratio (RTR) = root dry weight ÷ top dry weight, leaf weight ratio (LWR) = leaf dry weight ÷ total dry weight, stem weight ratio (SWR) = stem dry weight ÷ total dry weight, root weight ratio (RWR) = root dry weight ÷ total dry weight, and water use efficiency of productivity (WUE_p) = total irrigation volume retained by the substrate during the 5-week study ÷ total plant dry mass ($mL \cdot g^{-1}$).

Tops (stems and leaves) of plants from three replications were ground separately via a Foss Tecator Cyclotec™ 1093 sample mill (Analytical Instruments, LLC, Golden Valley, Minn.) to pass a ≤ 0.5 mm sieve. Mineral nutrient analysis of plant tissue samples was conducted by the NCDA, Agronomic Division. Total N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na concentrations were determined by methods described previously. Mineral nutrient content was calculated as follows: content = concentration ($mg \bullet g^{-1}$) x top dry weight (g); however, nutrient content results are not reported unless trends differed from concentration.

Experimental design and statistical analysis.

The physical property data were analyzed by regression and linear plateau models (SAS Inst. Inc., Cary, NC). The plant growth study was a 4 x 2 factorial in a randomized complete block design with six single plant replications. The factors were four substrates and two fertilizers, as described previously. All variables were analyzed using Proc ANOVA in SAS version 8.01 (SAS Inst. Inc., Cary, NC). Treatment comparisons between VC rates were made by single degree of freedom contrast tests, $P = 0.05$. Treatment comparisons between fertilizers were made by Fisher's Protected *LSD*, $P = 0.05$. No VC x fertilizer interactions were detected for root, stem, leaf, top or total dry weights; WUE_p; substrate solution pH; or mineral nutrient tissue concentration and content of N, K, Ca, Mg, B, Fe, Mn, Zn, Cu and Na, thus main VC effect results are reported. A significant VC x fertilizer interaction was detected for substrate solution EC, substrate solution concentrations of IN-N, P, and K at 6 and/or 30 DAP; and mineral nutrient tissue concentration and content of P and S; thus simple effect results are reported.

Results and Discussion

Substrate physical properties

TP, CC, AW, and D_b increased linearly with increasing rate of VC, whereas AS decreased linearly with increasing VC rate (Table 2). Increasing VC from 0% to 100% increased TP 7%, CC 26%, and AW 24%, and decreased AS 19%. UW followed a quadratic response with increasing VC rate with a calculated maximum UW at 54% VC. Increasing CC and decreasing AS associated with increasing rates of composted materials mixed with pine bark have been reported previously (Hildago *et al*. 2006; Jackson *et al*. 2005; Tyler *et al*. 1993).

The percentage of fine particles (≤ 0.5 mm) within each substrate was best described by a linear plateau model (if VC < 52%, then $y = 13.7x^2 - 0.164x + 51.5$), with fine particles decreasing from 14% (by wt) at 0% VC to a calculated plateau of 5.5% (by wt) at 52% VC (Table 3). The decrease of fine particles was correlated with decreasing AS ($r = 0.72$, P = <0.001). Data reported by Tyler *et al*. (1993) indicated a similar correlation between fine particles and AS of composted turkey litter amended pine bark. In contrast, the fine particle percentage of pine bark amended with sand, industrial clay, or pine chips increased as AS decreased (Handreck and Black 2002; Niemiera *et al*. 1994; Owen 2006; Wright and Browder 2005). These seemingly conflicting results may be attributed to properties of compost which have the ability to improve substrate structure by the formation of irregular-shaped aggregates which are not present with inorganic or recalcitrant amendments.

Basil production

<u>Substrate solution pH, EC, and nutrient concentrations</u>. VC rates from 5% to 20% resulted in a linear increase of substrate solution pH at all sample times (Table 4). VC at 5% had equivalent liming effects as 1.8 $kg{\cdot}m^{-3}$ dolomitic limestone (control), whereas 10% and 20% VC had greater liming effects than 1.8 $kg{\cdot}m^{-3}$ dolomitic limestone. Substrate solution pH in the 5% VC rate did not differ from the control, however, pH of the 10% and 20% VC was greater than the control. These results concur with Donald and Visser (1989) and Hidalgo and Harkess (2002) who reported solution pH increased with increasing rates of VC amended unlimed pine bark and peat moss, respectively. Similarly, other types of composts provide liming effects. Tyler *et al*. (1993) observed an increase of substrate solution pH with increasing rates of composted turkey (*Meleagris sp*.) litter amended to unlimed pine bark, and Vendrame and Moore (2005) reported an increase of extracted substrate pH with increasing rates of seaweed (genus unknown) or yard-waste compost amended to unlimed peat moss based substrates. Additionally, VC appeared to have more pH buffering capacity than dolomitic limestone at rates of 10% and 20%, as the change of pH from 6 to 35 DAP for the control was -0.71 units, whereas the change over the same time for 5%, 10%, and 20% VC were -0.40, -0.02, and -0.22 units, respectively. These data indicate that VC amended pine bark at rates as low as 5% will provide liming equivalencies and buffering capacity to that of 1.8 $kg{\cdot}m^{-3}$ dolomitic limestone. The pH buffering capacity associated with the VC is most likely due to the greater CEC associated with humic substances characteristic of composted materials (Handreck and Black 2002).

VC had no effect on EC (data not presented), however, fertilizer did affect EC (Table 5). On 6 and 14 DAP, substrate solutions from 19-5-9 had greater EC compared to 19-5-13 in VC treatments and the pine bark control. The EC values measured at 6 DAP in 19-5-9 were higher than the recommended maximum of 2.0 $dS \cdot m^{-1}$ (Bailey et al., 1999), however, EC dropped within acceptable ranges by 14 DAP. At 24 DAP, EC values from 19-5-9 were still greater than 19-5-13 within 5% and 20% VC rates, and the control. The elevated EC values of fertilizer 19-5-9 were due to differences in fertilizer prill coating formation which yielded a faster release rate than fertilizer 19-5-13. This is supported by substrate solution nutrient analysis collected on 6 and 30 DAP (Table 6). Regardless of the high initial EC values of 19-5-9, there was no significant difference in plant growth between the two fertilizers (data not presented).

Plant growth. The VC x fertilizer interaction was not significant, nor were there any main effect differences by fertilizer for root, stem, leaf, top, and total dry weights. Thus only main effect results for VC data are presented (Table 7). All dry weights (root, stem, leaf, top, and total) increased linearly with increasing VC rate, and 20% VC was significantly greater than the control. There were no significant differences in leaf area (mean = 1022 cm^2 ± 93), RTR (mean = 0.17 ± 0.008), LWR (mean = 0.57 ± 0.006), SWR (mean = 0.28 ± 0.005), or RWR (mean = 0.15 ± 0.006) (data not presented). Therefore, carbon allocation between the top and root was similar across all rates of VC.

Other researchers have reported increased plant growth when grown in VC amended pine bark and peat moss with and without additional fertilizer (Atiyeh *et al*. 2000; Atiyeh *et al*. 2001; Bachman and Davis 2000; Hidalgo *et al*. 2006; Hidalgo and Harkess 2002). These studies support results herein that a VC amended soilless substrate can increase plant growth even when nutrients were supplied at recommended quantities for the specific crop, indicating factors other than nutrients may be responsible for increased plant growth. Several hypotheses for the increased plant growth associated with VC amended substrates have been proposed including the presence of humic acids (Arancon *et al*. 2006b), microbial biomass activity (Arancon *et al*. 2006a), and improved physical properties (McGinnis *et al*. 2005). Perhaps the exact mechanism in which VC benefits plant growth has eluded researchers due to the complex interaction and synergistic effects of these factors, as suggested by Tomati and Galli (1995).

Water use efficiency. WUE_p was unaffected by VC x fertilizer interaction and fertilizer main effects (data not presented); thus, only VC main effects are presented (Table 7). WUE_p showed a linear decrease with increasing VC rate (less water was used to produce a gram of plant dry mass), and 20% VC was lower than the control. There was no significant difference in the total water volume applied per container (mean = 2788 ml ± 295) (data not presented), therefore the addition of VC resulted in more plant tissue without increasing irrigation water volume. The changes in WUE_p were correlated with changes in CC (r = 0.96, P = 0.011), AW (r = 0.99, P = 0.011), and AS (r = 0.99, P = 0.002). While best management practices such as irrigation timing and cyclic irrigation have been shown to improve WUE_p (Groves *et al*. 1998; Warren and Bilderback 2002), the data herein agree with findings by Owen (2006), in which substrate amendments that increas CC and AW can improve WUE_p. Practical implications of amending pine bark with 20% VC compared to a limed, non-VC amended control include equal volumes of irrigation water while yielding a larger crop or reducing irrigation volumes and production time by achieving an equivalent crop size earlier.

Nutritional status. No differences between top N tissue concentrations were detected between the VC treatments or the control (mean = 47.2 $mg \cdot g^{-1} \pm 1.8$) (data not presented), indicating N was not responsible for the increased plant growth observed with increasing VC rate. Additionally, top N concentration was greater than a sufficiency reference of 2.4 – 5.6 $mg \cdot g^{-1}$, reported for *Salvia splendens* Sellow ex. Schult. (salvia) and *Coleus x hybridus* Benth. (coleus), two species in the same family as basil, Labiatae (Mills and Jones 1996).

Likewise, top nutrient tissue concentration of K (mean = 42.4 $mg \cdot g^{-1} \pm 1.8$), Mg (mean = 4.8 $mg \cdot g^{-1} \pm 0.2$), Fe (mean = 108 $ug \cdot g^{-1} \pm 11$), Cu (mean = 23 $ug \cdot g^{-1} \pm 2.2$), Zn (mean = 191 $ug \cdot g^{-1} \pm 13$), B (34.4 $ug \cdot g^{-1} \pm 1.5$), or Na (mean = 724 $ug \cdot g^{-1} \pm 47$) were unaffected by substrate treatment, indicating uptake of these nutrients did not promote the increased plant growth observed with increasing VC rate. As with N, concentrations were within or greater than the reference leaf sufficiency ranges of salvia and coleus for K (2.9 – 5.9 $mg \cdot g^{-1}$), Mg (0.3 – 1.5 $mg \cdot g^{-1}$) Fe (49 – 300 $ug \cdot g^{-1}$), Cu (7 – 3549 $ug \cdot g^{-1}$), Zn (25 – 115 $ug \cdot g^{-1}$), B (0.3 – 75 $ug \cdot g^{-1}$), and Na (270 – 5198 $ug \cdot g^{-1}$) (Mills and Jones 1996).

A significant VC x fertilizer interaction was not detected for Ca and Mn, thus only VC effect results are presented. Top Ca concentration increased linearly with increasing VC rate (Table 8) and top Ca content showed similar trends (data not presented). Additionally, top Ca concentrations for all treatments were greater than the control (Table 8). Based on these data, VC was an excellent source of Ca, as limestone, the primary Ca source for horticultural crops, was not added to the VC amended substrates. In contrast, top Mn concentration decreased linearly with increasing VC rate (Table 8), and top Mn content showed similar trends (data not presented). This is most likely due to decreased Mn availability associated with increased pH (Havlin *et al*. 2005). This is further evidenced by the non significant difference in substrate pH between 5% VC and the control (Table 4).

There was a significant VC x fertilizer interaction for top tissue concentration of P and S, thus simple effect results are presented (Table 9). Substrate treatments did not affect top mineral P concentrations (mean = 6.4 $mg \cdot g^{-1} \pm 0.2$) of basil produced with 19-5-9, whereas substrate treatments did not affect top S (mean = 2.5 $mg \cdot g^{-1} \pm 0.08$) of basil produced with 19-5-13. The top mineral P concentration of basil produced with 19-5-13 decreased linearly with increasing VC rates (Table 9). In contrast, top mineral P content was unaffected by rates of VC (mean = 31.8 ± 4.4 mg). The decreased P concentrations associated with increased VC rates were probably a result of dilution due to an increased growth with increased VC, as a similar content of P was absorbed by all three treatments. The 19-5-13 control, however, had a significantly lower P concentration than VC treatments grown with 19-5-13 (Table 9). A similar response was observed for top mineral P content, where plants grown in the control (7.4 ± 0.7 mg) absorbed less P than plant grown in VC (reported above). It does not appear the low P concentration in the 19-5-13 control plants limited plant growth, as no difference was detected between growth of plants in the 19-5-9 and 19-5-13 controls (6.4 and 2.5 $mg \cdot g^{-1}$, respectively). Additionally, all substrate treatments have top P concentrations above the sufficiency range for salvia and coleus (Table 9). These data indicate fertilizer P rates may be reduced when substrates are amended with VC.

For basil produced with 19-5-9, greater S concentrations were observed in the control compared to 10% and 20% VC (Table 9), and top S content showed similar trends (data not presented). Top basil tissue S concentrations for all treatments were within or above the sufficiency ranges for salvia and coleus (Table 9).

Summary

In conclusion, VC amended pine bark provided liming effects and pH buffering, improved physical properties, improved WUE_P, increased plant growth of all tissues, and more than double the P concentration top tissue. Increased plant growth does not appear to be due to nutrients supplied by VC, however improvements in physical properties may be responsible for increased growth and improved WUEp.

These results lead to practical implications of containerized crop production in pine bark substrates amended with VC. First, the addition of dolomitic limestone to the pine bark can be eliminated due to the liming equivalencies associated with the VC. Second, the improvement of container capacity and available water will provide more water available for plant uptake between irrigation events, potentially reducing the possibility of plant stress due to low moisture between irrigation cycles. Third, the improved WUE_P allows more efficient use of the irrigation supply. Forth, the increased plant growth will result in a larger plant at the time of sale, or the reduced production time before the plant is ready for sale. And fifth, the greater P concentrations in plants grown with VC suggest that VC may be able to serve as the sole source of P, thus P fertilizer inputs can be eliminated.

Literature Cited

Arancon, N.Q., C.A. Edwards, and P. Bierman. 2006a. Influence of vermicomposts on field strawberries: Part 2. Effects on soil microbiological and chemical properties. Bioresource Technol. 97:831-840.

Arancon, N.Q., C.A. Edwards, S. Lee, and R. Byrne. 2006b. Effects of humic acids from vermicomposts on plant growth. European J. Soil Biol. 42:S65-S69.

Atiyeh, R.M., N.Q. Arancon, C.A. Edwards, and J.D. Metzger. 2002. The influence of earthworm-processed pig manure on the growth and productivity of marigolds. Bioresource Technol. 81:103-108.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2000. Earthworm-processed organic wastes as components of horticultural potting media for growing marigold and vegetable seedlings. Compost Sci. Util. 8:215-223.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2001. Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physiochemical properties and plant growth. Bioresource Technol. 78:11-20.

Bachman, G.R. and W.E. Davis. 2000. Growth of *Magnolia virginiana* liners in vermicompost-amended media. Proc. SNA Res. Conf., Forty-Fifth Annu. Rpt. p. 65-76.

Bailey, D., T. Bilderback, and D. Bir. 1999. Water considerations for container production of plants. N.C. Coop. Ext. Serv. Hort. Info. Lflt 557.

Bilderback, T.E., W.C. Fonteno, and D.R. Johnson. 1982. Physical properties of media composed of peanut hulls, pine bark, and peatmoss and their effects on azalea growth. J. Amer. Soc. Hort. Soc. 107:522-525.

Donald, D.G.M. and L.B. Visser. 1989. Vermicompost as a possible growth medium for the production of commercial forest nursery stock. Appl. Plant Sci. 3:110-113.

Eastman, B.R., P.N. Kane, C.A. Edwards. L. Trytek, B. Gunadi, A.L. Sterner, and J.R. Mobley. 2001. The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. Compost Sci. Util. 9:38-49.

Edwards, C.A. June 1995. Historical overview of vermicomposting. BioCycle 36:50-54.

Groves, K.M, S.L. Warren, and T.E. Bilderback. 1998. Irrigation volume, application, and controlled-release fertilizer II. Effect on substrate solution nutrient concentration and water efficiency in containerized plant production. J. Environ. Hort. 16:182-188.

Handreck, K. and N. Black. 2002. Growing media for ornamental plants and turf. 3rd ed. UNSW Press, Sydney.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertility: an introduction to nutrient management. 7th ed. Prentice Hall, N.J.

Hidalgo, P.R. and R.L. Harkess. 2002. Earthworm castings as a substrate for poinsettia production. HortScience 37:304-308.

Hidalgo, P.R., F.B. Matta, and R.L. Harkess. 2006. Physical and chemical properties of substrates containing earthworm castings and effects on marigold growth. HortScience 41:1474-1476.

Jackson, B.E., A.N. Wright, D.M. Cole, and J.F Sibley. 2005. Cotton gin compost as a substrate component in container production of nursery crops. J. Environ. Hort. 23:118-122.

Klute, A. 1986. Water retention: Laboratory methods, pp. 635–662. In: A. Klute (ed.). Methods of Soil Analysis: Part 1, Physical and Mineralogical Methods, 2nd ed. Amer. Soc. Agron. .Soil Science Sci. of Amer, Madison, Wis.

Ku, C.S.M and D.R. Hershey. 1992. Leachate electrical conductivity and growth of potted pointsettia with leaching fraction of 0 to 0.4. J. Amer. Soc. Hort. Sci. 116(5):802-806.

Mallin, M.A., and L.B. Cahoon. 2003. Industrialized animal production – a major source of nutrient and microbial pollution to aquatic ecosystems. Population and Envr. 5:369-385.

McGinnis, M., T. Bilderback, and S. Warren. 2005. Vermicompost: Improving water use efficiency in nursery crop production. Proc. SNA Res. Conf., Fiftieth Annu. Rpt. p.73-77.

Mills, H.A. and J. B. Jones, Jr. 1996. Plant Analysis Handbook II. A practical sampling, preparation, and analysis guide. Micromacro Publishing, Inc., Athens, GA.

Niemiera, A.X., T.E. Bilderback, and C.E. Leda. 1994. Pine bark physical characteristics influence pour-through nitrogen concentrations. HortScience 29:789-791.

Owen, Jr., J.S. 2006. Clay amended soilless substrates: Increase water and nutrient efficiency in containerized crop production. North Carolina State Univ., Raleigh, PhD Diss.

Tomati, U. and E. Galli. 1995. Earthworms, soil fertility, and plant productivity. Acta Zoologica Fennica 196:11-14.

Tyler, H.H., S.L. Warren, T.E. Bilderback, and W.C. Fonteno. 1993. Composted turkey litter: I. Effect on chemical and physical properties of a pine bark substrate. J. Environ. Hort. 11:131-136.

Vendrame, W. and K.K. Moore. 2005. Comparison of herbaceous perennial plant growth in seaweed compost and biosolids compost. Compost Sci. Util. 13:122-126.

Warren, S.L. and T.E Bilderback. 2002. Timing of low pressure irrigation affects plant growth and water utilization efficiency. J. Environ. Hort. 20:184-188.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227-229.

Wright R.D. and J.F. Browder. 2005. Chipped pine logs: A potential substrate of greenhouse and nursery crops. HortScience. 40:1513-1515.

TABLE 1.Chemical properties of vermicompost.

C	N	P	K	Ca	Mg	S	pH
(mg·g^{-1})							
290 ± 10[z]	16 ± 1	20 ± 0.1	0.7 ± 0.1	88 ± 2	2.8 ± 0.1	2.7 ± 0.4	6.87 ± 0.06

Fe	Mn	Zn	Cu	B	Na	EC
(ug·g^{-1})						(dS·m^{-1})
3108 ± 97	1173 ± 32	564 ± 2	122 ± 4.5	23 ± 1.1	405±16	1.25 ± 0.10

TABLE 2. Physical properties of vermicompost (VC) amended pine bark substrates.

VC rate (v/v)	Total porosity[z] (% vol)	Air space[y] (% vol)	Container capacity[x] (% vol)	Available water[w] (% vol)	Unavailable water[v] (% vol)	Bulk density ($g \cdot cc^{-3}$)
0%	80.5 ± 1.7[u]	34.0 ± 2.8	46.6 ± 1.6	17.8 ± 1.6	28.7 ± 0.4	0.17 [t]
5%	82.8 ± 0.2	35.0 ± 0.8	47.8 ± 0.8	16.7 ± 0.8	31.2 ± 0.5	0.18
10%	82.8 ± 0.3	30.1 ± 0.5	52.7 ± 0.4	20.3 ±0.4	32.4 ± 0.3	0.18
20%	81.7 ± 0.4	27.1 ± 2.0	54.7 ± 1.9	23.2 ± 1.9	31.5 ± 0.9	0.19
40%	83.0 ± 0.6	27.1 ± 1.9	55.9 ± 1.6	20.8 ± 1.6	35.2 ± 1.1	0.21
60%	84.7 ± 1.2	23.7 ± 1.9	60.9 ± 1.0	27.0 ± 1.0	33.9 ± 0.9	0.22
80%	86.1 ± 0.7	20.6 ± 1.8	65.5 ± 2.0	30.7 ± 2.0	34.8 ± 0.9	0.24
100%	87.6 ± 0.3	15.3 ± 1.6	72.4 ± 1.8	41.3 ± 1.8	31.1 ± 1.2	0.25
Target range[s]	50-85	10-30	45-65	25-35	25-35	0.19-0.27
Linear	<0.0001	<0.0001	<0.0001	<0.0001	0.0296	<0.0001
Quadratic	0.3132	0.9759	0.6432	0.0041	<0.0001	0.1598

[z]Based upon percent volume of a 7.6 x 7.6 cm core at 0 kPa.

[y]Measured as percent volume air of a 7.6 x 7.6 cm core at 0 kPa.

[x]Measured as percent volume water of a 7.6 x 7.6 cm core after drainage at 0 kPa.

[w]Calculated by container capacity – unavailable water.

[v]Based upon percent volume water retained of a 7.6 x 7.6 cm core at 1500 kPa.

[u]Each mean ± 1 SE based on four observations.

[t]All SE of D_b were <0.003

[s]Yeager et al., 1997

[r]Based on regression analysis. *P* values listed.

TABLE 3. Particle size distribution of vermicompost (VC) amended pine bark substrates.

VC rate (v/v)	Particle size range (mm)							
	>6.3	6.3-2.0	2.0-0.70	0.71-0.50	0.50-0.25	0.25-0.11	<0.11	Fines[z]
	(% wt)							
0%	6.83 ± 0.19[y]	43.13 ± 1.47	27.33 ± 0.67	8.41 ± 0.24	8.20 ± 0.24	3.78 ± 0.10	2.30 ± 0.10	14.29 ± 0.43
5%	6.83 ± 0.11	42.69 ± 0.18	32.64 ± 0.18	7.19 ± 0.10	6.57 ± 0.08	2.72 ± 0.03	1.35 ± 0.02	10.64 ± 0.12
10%	8.57 ± 0.59	40.04 ± 0.61	28.59 ± 0.20	9.63 ± 0.16	9.02 ± 0.10	3.04 ± 0.05	1.10 ± 0.03	13.17 ± 0.12
20%	8.88 ± 0.69	38.40 ± 0.57	31.26 ± 0.58	9.84 ± 0.29	7.91 ± 0.36	2.86 ± 0.38	0.84 ± 0.01	11.61 ± 0.55
40%	13.39 ± 1.71	37.55 ± 0.61	35.26 ± 1.52	7.22 ± 0.19	4.41 ± 0.11	1.53 ± 0.01	0.64 ± 0.04	6.58 ± 0.16
60%	11.77 ± 1.84	41.05 ± 1.01	37.31 ± 1.54	4.65 ± 0.10	3.26 ± 0.12	1.31 ± 0.04	0.64 ± 0.03	5.20 ± 0.19
80%	8.73 ± 0.89	32.49 ± 1.37	47.23 ± 1.49	6.39 ± 0.11	3.35 ± 0.06	1.25 ± 0.04	0.56 ± 0.03	5.16 ± 0.13
100%	19.07 ± 1.90	36.22 ± 0.89	34.67 ± 1.53	4.57 ± 0.11	3.14 ± 0.05	1.49 ± 0.05	0.83 ± 0.03	5.46 ± 0.12
Linear	<0.001	<0.001	<0.001	<0.001	NS	<0.001	<0.001	<0.001
Lin-Plateau	NS	<0.001	NS	NS	0.007	0.002	0.001	0.002

[z]Particle size <0.5mm.

[y]Each mean ± 1 SE based on four observations.

[x]Based on regression analysis. *P* values listed. NS = *P* values > 0.05.

TABLE 4. Effect of vermicompost (VC) amended pine bark substrate on substrate solution pH.

VC rate[z] (v/v)	Substrate solution pH Days after planting				
	6	14	24	30	35
5%	4.70 ± 0.04[y]	4.60 ± 0.34	4.80 ± 0.06	4.66 ± 0.08	4.30 ± 0.17
10%	5.64* ± 0.08	5.06 ± 0.23	5.58* ± 0.05	5.64* ± 0.17	5.62* ± 0.25
20%	6.13* ± 0.10	5.89* ± 0.30	6.13* ± 0.05	6.31* ± 0.06	5.91* ± 0.06
Control (0%)	4.87 ± 0.10	4.38 ± 0.14	4.99 ± 0.10	4.52 ± 0.11	4.16 ± 0.09
Contrasts[x]					
VC linear	<0.001	0.001	<0.001	<0.001	<0.009

[z]Vermicompost rates averaged over both fertilizer treatments (19-5-9 and 19-5-13).

[y]Each mean ± 1 SE based on 8 observations.

[x]Comparisons made by single degree of freedom contrast tests; control not included for linear contrast. *P* values listed.

*Significantly different from the control based on single degree of contrast tests at P=0.05.

TABLE 5. Effect of vermicompost (VC) amended pine bark substrate and fertilizer on substrate solution electrical conductivity (EC).

VC rate (v/v)	DAP[z]	Substrate solution EC ($dS \cdot m^{-1}$) Fertilizer[y] 19-5-9	19-5-13
5%	6	2.45 a ± 0.01[x]	0.53 b ± 0.02
	14	1.70 a ± 0.15	0.62 b ± 0.03
	24	1.41 a ± 0.13	0.76 b ± 0.05
	30	1.12 a ± 0.09	1.02 a ± 0.15
	35	0.96 a ± 0.06	0.93 a ± 0.14
10%	6	2.11 a ± 0.27	0.59 b ± 0.04
	14	1.87 a ± 0.07	0.68 b ± 0.06
	24	1.38 a ± 0.12	1.08 a ± 0.17
	30	1.26 a ± 0.12	1.20 a ± 0.38
	35	1.18 a ± 0.06	1.42 a ± 0.33
20%	6	2.35 a ± 0.04	0.56 b ± 0.03
	14	2.08 a ± 0.16	0.61 b ± 0.02
	24	1.62 a ± 0.08	0.87 b ± 0.06
	30	1.17 a ± 0.05	0.98 a ± 0.21
	35	1.05 a ± 0.18	0.83 a ± 0.20
Control (0%)	6	1.83 a ± 0.54	0.34 b ± 0.02
	14	1.71 a ± 0.05	0.46 b ± 0.03
	24	1.23 a ± 0.07	0.49 b ± 0.06
	30	0.99 a ± 0.11	0.80 a ± 0.07
	35	0.88 a ± 0.11	0.83 a ± 0.12

[z]DAP = days after planting.

[y]Fertilizer comparisons made within rows by Fisher's protected LSD, *P*=0.05. Means within rows followed by the same letter are not significantly different from each other.

[x]Each mean ± 1 SE based on four observations.

TABLE 6. Effect of vermicompost (VC) amended pine bark substrate and fertilizer on selected substrate solution nutrient concentrations.

		Fertilizer[z]					
VC rate		19-5-9[x]	19-5-13	19-5-9	19-5-13	19-5-9	19-5-13
(v/v)	DAP[y]	IN-N[x] ($mg \cdot L^{-1}$)		P ($mg \cdot L^{-1}$)		K ($mg \cdot L^{-1}$)	
5%	6	99 a ± 10[w]	36 b ± 10	102 a ± 4	73 b ± 10	310 a ± 25	61 b ± 3
	30	29 b ± 11	116 a ± 16	58 a ± 17	33 a ± 3	70 a ± 28	18 a ± 2
10%	6	83 a ± 9	36 b ± 14	64 a ± 7	61 a ± 11	154 a ± 19	50 b ± 6
	30	21 a ± 7	114 a ± 54	61 a ± 10	47 a ± 11	48 a ± 15	23 a ± 7
20%	6	102 a ± 3	28 b ± 13	79 a ± 5	45 b ± 2	266 a ± 36	48 b ± 3
	30	23 b ± 8	95 a ± 27	44 a ± 5	26 b ± 3	60 a ± 9	12 b ± 4
Control	6	85 a ± 6	43 b ± 15	62 a ± 7	11 b ± 1	202 a ± 18	39 b ± 3
(0%)	30	24 b ± 10	104 a ± 13	18 a ± 8	2 a ± 1	48 a ± 16	11 a ± 2

[z]Fertilizer comparisons within rows within mineral nutrient by Fisher's protected LSD, P=0.05. Means within rows followed by the same letter are not significantly different from each other.

[y]DAP = days after planting.

[x]IN-N = inorganic N fractions NO_3 and NH_4

[w]Each mean ± 1 SE based on four observations.

TABLE 7. Effect of vermicompost (VC) amended pine bark on dry weights and water use efficiency of Genovese basil grown for 5 weeks.

VC rate[z] (v/v)	Root dry wt (g)	Stem dry wt (g)	Leaf dry wt (g)	Top dry wt[y] (g)	Total dry wt[x] (g)	Water use efficiency[w] ($mL \cdot g^{-1}$)
5%	0.48 ± 0.08[v]	1.03 ± 0.08	2.02 ± 0.18	3.05 ± 0.26	3.52 ± 0.33	673* ± 56
10%	0.69 ± 0.08	1.18 ± 0.09	2.34 ± 0.19	3.51 ± 0.27	4.20 ± 0.33	560 ± 40
20%	0.80* ± 0.07	1.40* ± 0.09	2.89* ± 0.14	4.29* ± 0.22	5.09* ± 0.28	464* ± 25
Control (0%)	0.57 ± 0.07	1.11 ± 0.07	2.35 ± 0.15	3.46 ± 0.21	4.03 ± 0.26	567 ± 29
Contrasts[u]						
VC linear	0.003	0.004	0.001	0.001	0.001	<0.001

[z]Vermicompost rates averaged over both fertilizer treatments (19-5-9 and 19-5-13).

[y]Top dry weight = stem dry weight + leaf dry weight.

[x]Total dry weight = root dry weight + stem dry weight + leaf dry weight.

[w]Water use efficiency (WUE) = total volume water retained in container (ml) ÷ total dry weight (g).

[v]Each mean ± 1 SE based on 12 observations.

[u]VC main effect comparisons made by single degree of freedom contrast tests. Controls not included with linear contrast. *P* values listed.

*Significantly different from the control based on single degree of contrast tests at *P*=0.05.

TABLE 8. Effect of vermicompost (VC) amended pine bark on top calcium (Ca) and manganese (Mn) concentration of Genovese basil.

VC rate[z] (v/v)	Ca ($mg \cdot g^{-1}$)	Mn ($ug \cdot g^{-1}$)
5%	20.6* ± 2.1[y]	538.6 ± 82.7
10%	24.8* ± 2.1	348.0* ± 47.6
20%	27.4* ± 2.6	168.5* ± 17.5
Control (0%)	12.2 ± 1.9	524.1 ± 34.3
Contrasts[x]		
VC linear	<0.001	<0.001
Sufficiency levels[w]	1.0- 1.65	30- 325

[z]Vermicompost rates averaged over both fertilizer treatments (19-5-9 and 19-5-13).

[y]Each mean ± 1 SE based on six observations.

[x]VC main effect comparisons made by single degree of freedom contrast tests. Controls not included with linear contrast. *P* values listed.

[w]Leaf sufficiency range of two Labiatae genuses, *Salvia spledens* Sellow ex. Schult. and *Coleus x hybridus* Benth., Mills and Jones (1996).

*Significantly different from the control based on single degree of contrast tests at *P*=0.05.

TABLE 9. Effect of vermicompost (VC) amended pine bark substrates on top phosphorus concentration grown with 19-5-13 and top sulfur concentration grown with 19-5-9 of Genovese basil.

VC rate[z] (v/v)	P[z] ($mg{\cdot}g^{-1}$)	S[y] ($mg{\cdot}g^{-1}$)
5%	8.8* ± 0.5[x]	5.2 ± 0.6
10%	7.7* ± 0.4	3.1* ± 0.2
20%	6.9* ± 0.2	2.9* ± 0.4
Control (0%)	2.5 ± 0.2	7.6 ± 1.2
Contrasts[x]		
VC linear	0.007	0.121
Sufficiency levels[w]	0.3-1.26	0.73-1.01

[z]Phosphorus concentrations for plants grown in fertilizer 19-5-13.

[y]Sulfur concentrations for plants grown in fertilizer 19-5-9.

[x]Each mean ± 1 SE based on three observations.

[w]VC simple effect comparisons made by single degree of freedom contrast tests. Control not included with linear contrast. *P* values listed.

[v]Leaf sufficiency range of two Labiatae genuses, *Salvia spledens* Sellow ex. Schult. and *Coleus x hybridus* Benth., Mills and Jones (1996).

*Significantly different from the control based on single degree of contrast tests at *P*=0.05.

Chapter 2

Effects of Vermicompost Amended Pine Bark on Containerized Nursery Crop Production

(In the format appropriate for submission to HortScience)

Effects of Vermicompost Amended Pine Bark on Containerized Nursery Crop Production

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Received for publication _____________. This research was funded in part by the North Carolina Agricultural Research Service (NCARS), Raleigh, NC 27695-7643 and the Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Fellowship. Use of trade names in this publication does not imply endorsement by the NCARS or EPA of products named nor criticism of similar ones not mentioned. Appreciation is extended to William M. Reece and Mary Lorscheider for technical assistance and Cavelle Brownie for statistical assistance. From a thesis submitted by M.S.M. in partial fulfillment of the requirements for the PhD degree.

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Subject Category: Soil Management, Fertilization, and Irrigation

Effects of Vermicompost Amended Pine Bark on Containerized Nursery Crop Production

Additional index words: Available water, container capacity, *Coreopsis verticillata*, *Cotoneaster dammeri*, EC, *Gardenia jasminoides*, hog manure, herbaceous, perennial, pH, physical properties, water use efficiency of productivity, worm castings, *Verbena canadensis*

Abstract. The objectives of this study were to determine the effects of vermicompost (VC) amended pine bark (PB) on substrate physical and chemical properties, water use efficiency of productivity (WUE_P), and plant growth of four nursery crop species. Several experiments were conducted to accomplish these objectives, including (1) the determination of substrate physical properties compacted to *in situ* bulk density at 53 and 164 days after potting and (2) four plant growth experiments with two woody species, *Cotoneaster dammeri* C.K. Schneid. 'Stogholm' (cotoneaster) and *Gardenia jasminoides* (L.) Merr.'Chuck Hayes' (gardenia), and two herbaceous species, *Verbena canadensis* L 'Purple Homestead' (verbena), and *Coreopsis verticillata* L 'Moonbeam' (coreopsis). Experimental substrate treatments were 0%, 10%, 20%, 40%, and 60% VC amended PB (v/v) and an 11% sand amended PB (v/v) (hereafter referred to as PBS). The PBS treatment received 1.8 $kg \cdot m^{-3}$ dolomitic limestone and served as an industry standard. Container capacity and available water increased linearly and air space decreased linearly with increasing VC rate, whereas

unavailable water was unaffected at 53 and 164 days. Total porosity increased linearly with increasing VC rate at 53 days. Substrate solution pH of cotoneaster and verbena followed a quadratic plateau model. An average substrate solution pH range from 5.5 to 6.0 was achieved with 21% to 29% VC (cotoneaster) and 25% to 35% VC (verbena). Top and root dry weight of cotoneaster increased linearly with increasing VC rates whereas verbena growth was not affected by increasing VC rate. Cotoneaster top dry weight grown in ≥ 20% VC and verbena root, flower bud, and vegetative top dry weight grown in 20% VC were greater than PBS. Top dry weight of cotoneaster and verbena produced in 0% VC was lower than PBS. Gardenia and coreopsis top dry weight decreased with increasing VC rate. Gardenia root and top dry weights at 40% and 60% VC and coreopsis top dry weight at 0% and 60% VC were less than PBS. The WUE_p for cotoneaster and verbena were unaffected by increased VC rate, however, WUE_p of verbena at 20% VC was improved compared to PBS. Top cotoneaster nitrogen, calcium, magnesium, boron, iron, and copper nutrient concentrations were unaffected by VC rate. Top cotoneaster potassium, sulfur, manganese, zinc, and sodium decreased with increasing VC rates whereas, phosphorus concentration increased with increasing VC rate. Top verbena mineral nutrient concentration of nitrogen, phosphorus, magnesium, sulfur, iron, copper, and sodium concentrations were unaffected by VC rate. Top verbena potassium, manganese, and zinc decreased with increasing VC rates whereas, verbena top calcium and boron concentration increased with increasing VC rate. We conclude that (1) 20% VC amended PB will provide greater or equivalent plant growth WUE_P to PBS and that 20% VC will provide adequate liming equivalencies thus precluding the need to amend the substrate with dolomitic limestone.

Vermicomposting, a process by which earthworms and bacteria stabilize organic waste during an aerobic, non-thermophillic process, produces vermicompost (VC) (Edwards, 1995). The production of VC is a proven technology and an economical approach for animal waste management (Edwards, 1995) and eliminates pathogens to United States Environmental Protection Agency Class A criteria (Eastman et al., 2001). Due to its ability to improve physical properties of soilless substrates and to provide plant available nutrients, a target of potential use of VC has been containerized horticultural crops (Edwards, 1995; Hidalgo et al., 2006).

Research investigating the response of plants grown in VC amended peat moss (PM) based substrates in combination with sufficient fertilizer nutrients has yielded mixed results, seemingly due to the waste source from which the VC was derived and/or the crop species produced. Atiyeh et al. (2000) reported greater top dry weight of 3-week old tomato (*Lycopersion esculentum* Mill.) seedlings produced in VC derived from hog (*Sus* sp.) manure at 10% VC compared to seedlings produced in 10% VC derived from food waste. Hidalgo and Harkess (2002b) reported greater growth of poinsettia (*Euphorbia pulcherrima* 'Freedom Red' Willd.) grown in 25% VC derived from sheep (*Ovine aries* L.) and cattle (*Bos taurus* L.) manure compared to VC derived from horse (*Equus caballus* L.) manure. Differential responses between species was reported by Paul and Metzger (2005), where ~9-week old tomato and eggplant (*Solanum melongena* L.) transplants had similar top dry weight when grown in 0%, 10%, and 20% VC derived from cattle manure whereas. In contrast, pepper (*Capsicum annuun* L.) top dry weight was less for plants grown in 10% VC compared to 0% and 20%.

Others have reported increased plant growth when grown in VC amended PM based substrates. In general, VC rates ≤ 60% (v/v) have resulted in equivalent or greater plant growth compared to plant growth in commercial production soilless substrates. Several studies have investigated the effect of VC rate amended to PM based substrates on floriculture crop growth. Top dry weights of ~70 day old chrysanthemum (*Dendranthema x grandiflora* (Ramat.) Kitamura 'Miramar') and ~84 day poinsettia grown in VC derived from sheep, cattle, and horse manure amended PM substrates increased quadratically with increasing VC rates (Hidalgo and Harkess, 2002a, 2002b). Based on the quadratic model, maximum top growth ranged from 44% to 59% VC and depended on the VC source and species. Atiyeh et al. (2002) reported top and root dry weights of 121-day old marigold (*Tagetes patula* L. 'Queen Sophia') grown in VC amended PM substrates ranging from 0% to 100% VC (derived from hog manure) responded quadratically to increasing rate of VC rate. Maximum growth was calculated to occur at 35% and 57% VC for top and root dry weights, respectively.

Most research with VC has been done with greenhouse crops with VC amended to PM based substrates. However, nursery crops comprise a significant part of the containerized horticulture crop industry and incorporation of VC in nursery crop soilless substrates may provide a potential market for use of VC as well as benefits to the nursery industry. Pine bark (PB) is the soilless substrate of choice for most nursery crops in the southeast, and the incorporation of VC into PB may benefit nursery crop production. The objectives of this study were to determine the effect of VC (derived from hog manure) amended PB on substrate physical properties, WUE_P and plant growth of several common nursery crop species grown in a simulated nursery setting.

Materials and Methods

Substrate treatments, chemical properties, and physical properties. Five substrate treatments included aged (~1 year), milled PB (<1.25 cm) amended with VC (Vermicycle Organics, Wilson, NC) derived from hog manure at 0%, 10%, 20%, 40%, and 60% (v/v) with no additional amendments. In addition, an 8 PB : 1 sand (v/v) substrate amended with pulverized dolomitic limestone at 1.8 $kg \cdot m^{-3}$ (hereafter referred to as PBS) served as an industry standard treatment. Substrates were blended with a 0.76 m^{-3} rotary mixer (Bouldin & Lawson, LLC, McMinnville, Tenn.).

VC arrived in 22.7 kg bags. One sample was collected from each bag (22 bags total), and three samples of PB were collected for chemical analysis. Prior to mixing the substrate treatments, all bags of VC were blended. Mineral nutrient analysis of VC and PB was conducted by the N.C. Department of Agriculture and Consumer Services (NCDA & CS), Agronomic Division, Raleigh (Table 1). Prior to analysis, samples were dried at $60^{o}C$ and ground (ED-5 Wiley Mill; Thomas Scientific, Swedesboro, N.J.) to pass through a 1 mm screen (Campbell and Plank, 1992). Total carbon (C) and nitrogen (N) concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500; CE Elantech Instruments, Milan, Italy) (Campbell, 1992). Total phosphorus (P), potassium (K), Ca, Mg, sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and sodium (Na) concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Wellesley, Mass.), following open-vessel HNO_3 digestion in a microwave digestion system (CEM Corp.; Matthews, NC) (Donohue and Aho, 1992). Electrical conductivity (EC) was determined using a 1 substrate : 2 distilled water extract (v/v), and pH was determined using a 1 substrate : 1 distilled water extract (v/v). Cation exchange capacity (CEC) was determined by summation of basic cations (excluding sodium) and buffer acidity (Mehlich et al., 1976).

Physical property analyses were conducted at the Horticultural Substrates Laboratory, Department of Horticultural Science, N. C. State Univ., Raleigh. On 14 May 2004, eight 347.5 cm^3 cylindrical aluminum rings (7.6 cm dia, 7.6 cm ht) and 10 101.4 cm^3 cylindrical aluminum rings (7.6 cm dia., 2.2 cm ht) of each substrate were inserted into individual 3.8 L fallow containers and placed on a simulated nursery pad under micro irrigation. On 4 July 2004 [53 days after initiation (DAI)] and 25 October 2004 (164 DAI), four 347.5 cm^3 cylinders and five 101.4 cm^3 cylinders with intact, naturally compacted substrates were extracted. With the exception of the 347.5 cm^3 cylinders extracted at 53 DAI, extracted cores were used to determine physical properties. The 347.5 cm^3 cylinders extracted at 53 DAI were repacked to the *in situ* bulk density determined from the extracted cores, according to procedures described in McGinnis (2007). Physical properties [total porosity (TP), air space (AS), container capacity (CC), available water (AW), unavailable water (UW), bulk density (D_b), and particle size distribution] were measured as described by Tyler et al. (1993).

Plant material and fertilizers. Two woody and two herbaceous perennial species of nursery crops were evaluated: *Cotoneaster dammeri* C.K. Schneid. 'Stogholm' (cotoneaster), *Gardenia jasminoides* (L.) Merr.'Chuck Hayes' (gardenia), *Verbena canadensis* L 'Purple Homestead' (verbena), and *Coreopsis verticillata* L 'Moonbeam' (coreopsis). All crops were grown in 3.8 L black plastic containers in substrate treatments described previously. Rooted stem cuttings of the woody species, cotoneaster and gardenia, [(propagated and grown in 213 cm^3 size cells, 5.4 cm x 5.4 cm x 7.3 cm) Traymasters Rose Pots, MacKenzie Nursery Supply Inc., Perry, OH)] were potted on 12 May 2004 and topdressed with controlled release fertilizer (CRF) 17N-2.2P-8.3K (17-5-10, 6 mo., 9.06% ammonical N, 8.04% nitrate N, blended with micronutrients) (Harrell's Fertilizer Inc., Lakeland, FL) at a rate of 5 g N per 3.8 L container (31.9 g fertilizer) on 18 May 2004. The herbaceous perennial species were obtained as plugs from Ball Seed Co. (Chicago, IL). Verbena (vegetatively propagated) and coreopsis (seed propagated) were potted on 27 July 2004 and topdressed with CRF 19N-2.2P-7.5K (19-5-9, 3-4 mo., 1.96% ammonical N, 10.01% urea N, and 7% water insoluble N, blended with micronutrients) (Harrell's Fertilizer Inc.) at a rate of 3 g per 3.8 L container (15 g fertilizer) on 1 August 2004. Plants were grown on a gravel pad at the Horticulture Field Lab at N. C. State Univ., Raleigh.

Irrigation. Irrigation was applied via pressure compensated spray stakes (Acu-Spray Stick; Wade Mfg. Co., Fresno, CA; 200 $ml \cdot min^{-1}$) with the daily total volume divided into three cycles. An early morning irrigation regime was followed from 12 May 2004 until 5 July 2004 with irrigation applied at 0300, 0500, and 0700 HR. Starting on 6 July 2004, irrigation was applied at 1200, 1500, and 1800 HR as the higher VC rates (40% and 60%) were becoming very dry during the day, resulting in a hydrophobic substrate which was difficult to rewet during the following irrigation cycle. A leaching fraction (LF) of 0.2 was targeted for cotoneaster and verbena according to the following equation: LF = volume leached ÷ volume applied. Volumes applied and leached were measured biweekly and irrigation volume was adjusted to maintain the 0.2 LF for cotoneaster and verbena. Gardenia and coreopsis were on the same irrigation lines as cotoneaster and verbena, respectively, thus irrigation volumes could not be manipulated to achieve a target LF of 0.2. The actual measured LFs for cotoneaster, verbena, gardenia, and coreopsis were 0.17, 0.19, 0.41 and 0.24, respectively.

Substrate solution pH and EC measurements. Substrate solution samples were collected approximately every two weeks from one subsample per plot of cotoneaster and verbena using the pour through nutrient extraction procedure (Wright, 1986). Substrate solution pH and EC measurements were obtained using an Acument pH/eV benchtop meter (Fischer Scientific, Springfield, N.J.).

Plant growth, nutritional status, and water use efficiency. On 9 Sept. 2004 (120 DAP), two subsamples per plot of cotoneaster and gardenia were harvested and partitioned into roots (one subsample for gardenia) and tops (tops = stems + leaves). On 10 Sept. 2001 (40 DAP), two subsamples per plot of verbena and coreopsis were harvested. Verbena was partitioned into roots, flower buds, and vegetative tops (vegetative tops = stems + leaves), and coreopsis into tops (tops = stems + leaves + buds + flowers) were harvested. Substrate was removed from roots using a high pressure water stream, and plants were dried at 65°C to constant mass (5 d) prior to obtaining dry weights of all segregated parts. The following variables were calculated as applicable to plant partitioning by species: total dry weight = top dry weight + root dry weight (g), root to top ratio (RTR) = root dry weight ÷ top dry weight, and water use efficiency of productivity (WUE_p) = total irrigation volume retained by the substrate during the study ÷ total plant dry mass ($mL{\cdot}g^{-1}$). WUE_p was determined only for cotoneaster and verbena.

The top plant tissue of cotoneaster, gardenia, and coreopsis from one subsample per plot and top plant tissue of verbena from two subsamples per plot were ground separately via a Foss Tecator Cyclotec™ 1093 sample mill (Analytical Instruments, LLC, Golden Valley, Minn.) to pass ≤ 0.5 mm sieve. Cotoneaster and gardenia tops were initially ground with a Model 4 bench, 1HP Wiley Mill (Thomas Scientific, Swedensboro, N.J.) to pass through a ≤ 6 mm sieve before passing through the Cyclotec. Tissue samples were analyzed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na by the NCDA & CS, Agronomic Division, by methods described previously.

Photosynthesis and stomatal conductance. On 23 Sept. 2004 between 0900 and 1100 HR, net CO_2 assimilation (P_n) (µmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) and stomatal conductance (g_s) (mol $H_2O \cdot m^{-2} \cdot s^{-1}$) measurements for cotoneaster were obtained using a LI-6400 gas analyzer (LI-COR, Lincoln, Nebr.). Water use efficiency of photosynthesis (WUE_{Pn}) was calculated as follows: WUE_{Pn} (mol $H_2O \cdot \mu mol^{-1}$ CO_2) = g_s (mol $H_2O \cdot m^{-2} \cdot s^{-1}$) ÷ P_n (µmol $CO_2 \cdot m^{-2} \cdot s^{-1}$). Sample chamber relative humidity levels were adjusted to mimic ambient relative humidity levels. Cotoneaster measurements were taken on the terminal 8 cm of growth on a southern exposed branch with ambient light at ~1600 µmol$\cdot m^{-2} \cdot s^{-1}$ PAR. The measured field conditions were as follows (n=24): vapor pressure deficit (VPD) = 2.32 ± 0.03 kPa, percent relative humidity (sample chamber) = 46.6 ± 0.29, CO_2 (sample chamber) = 374 ± 0.88 uL$\cdot L^{-1}$, and PAR = 1591 ± 36 µmol$\cdot m^{-2} \cdot s^{-1}$. On 24 Sept. 2004 between 1000 and 1200 HR, P_n and g_s measurements for verbena were obtained using a LI-6400 gas analyzer (LI-COR). Sample chamber relative humidity levels were adjusted to mimic ambient relative humidity levels. Verbena measurements were taken on the terminal 8 cm of growth on a southern exposed stem with ambient light at ~2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PAR. The measured field conditions were as follows (n=24): VPD = 4.02 ± 0.04 kPa, percent relative humidity (sample chamber) = 33.65 ± 0.22, CO_2 (sample chamber) = 384 ± 0.73 $uL \cdot L^{-11}$, and PAR = 2063 ± 11 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Experimental design and statistical analysis. Each species represented an independent study. Each study was a randomized complete block design with six substrate treatments (described previously) and four blocks with four plants per block. All data were subjected to analysis of variance and regression or non-linear regression analysis, and VC treatment comparisons to the control (PBS) were made by single degree of freedom contrast tests with SAS version 9.1 (SAS Inst. Inc., Cary, NC). The 0% VC treatment was excluded from regression analysis when necessary to eliminate misleading results due to poor performance of plants in 0% VC. Physical property data were analyzed by regression and VC treatment comparisons to the control (PBS) were made by single degree of freedom contrast test (SAS version 9.1). Differences were considered significant at the 10% probability level to minimize type II error (Marini, 1999).

Results and Discussion

Substrate physical properties. At 53 and 164 DAI, CC and AW increased linearly and AS decreased linearly with increasing VC rate, whereas UW was unaffected by VC rate (Tables 2 and 3). TP increased quadratically with increasing rates of VC at 53 DAP, however, no relationship between TP and VC rate at 164 DAP was observed. Similar results with freshly packed VC amended PB (≤ 1.27 cm) was reported by McGinnis (2007). In addition, other researchers have reported increased CC and decreased AS when PB was amended with composted materials such as vermicomposted cow manure (Hidalgo et al., 2006), composted cotton (*Gossypium* sp. L.) gin waste (Jackson et al., 2005), and composted turkey (*Meleagris gallopavo* L.) litter (Tyler et al., 1993). D_b increased linearly with increasing VC rate at 53 DAP however, D_b was unaffected by VC rate at 164 DAP (Tables 2 and 3).

At 53 DAI, TP, UW (except 20% VC), and D_b at all VC rates were significantly greater than PBS, whereas CC and AW were only greater than PBS at 20%, 40%, and 60% VC; and 0%, 20%, and 60% VC, respectively. However, by 164 DAI, only D_b was different from PBS at all rates of VC. TP and CC differed from PBS only at rates ≥40%, whereas UW was different from PBS at 0%, 20%, and 60% VC. AW was similar to PBS at all rates of VC. These changes in physical properties may be attributed to the decomposition of substrate materials occurring with time, resulting in homogeny of physical properties between substrate treatments (Bilderback et al., 2005).

Substrate solution pH. The effect of VC rate on cotoneaster substrate solution pH followed a quadratic plateau model for all seven samples times (Table 4). A calculated maximum pH ranged from 7.1 (30% VC) to 6.1 (35% VC) at 14 and 79 DAP, respectively. To achieve a target pH of 5.5 to 6.0 recommended by Handreck and Black (2002) for most containerized nursery crops, these models estimated 17% to 19% VC would be needed at 2, 14, 28, 42, and 56 DAP, whereas 27% to 29% VC would be needed at 79 and 98 DAP. At ≥ 40% VC, substrates solution pH values were greater than 7.0 at 14, 28, and 42 DAP. Elevated pH values may cause micronutrient deficiencies in some species (Havlin et al., 2005). Verbena substrate solution pH also increased according to a quadratic plateau model with increasing VC rate with calculated maximum pH values of 6.2 (37% VC), 6.3 (36%VC), 6.0 (56%VC), and 7.2 (62% VC) at 4, 13, 23, and 58 DAP, respectively (data not presented). A recommended target substrate solution pH of 5.5 – 6.0 estimated by these models would be 24% to 34% VC at 4, 13, and 58 DAP. Hidalgo and Harkess (2002a) reported substrate solution pH increased linearly with increasing rates of VC derived from sheep, cattle, and horse manure when amended to an unlimed PM substrate. The various mechanisms by which organic residues provide liming effects are outlined by Mokolobate and Haynes (2002).

Substrate solution EC. Cotoneaster substrate solution EC increased linearly with increasing VC rate at 2, 28, 42, and 98 DAP (Table 5). With the exception of 2.5 $dS \cdot m^{-1}$ at 2 DAP for 60% VC, all EC measurements were below the level of concern of 2.0 $dS \cdot m^{-1}$ suggested by Bailey et al. (1999). Substrate solution EC for ≥ 20% VC were greater than PBS on 2 DAP (before fertilizer was applied), while only EC of 60% VC was greater than PBS on 14, 28, 42, and 98 DAP (after fertilizer was applied) (Table 5). No EC differences compared to PBS were detected for any other VC treatments. indicating elevated EC levels may be a concern only at rates of ≥ 60% VC. Verbena substrate solution EC followed similar trends as cotoneaster (data not presented).

Plant growth. Cotoneaster root and top dry weight increased linearly with increasing VC rate (Table 6). Top dry weights of cotoneaster produced in ≥ 20% VC were greater than cotoneaster grown in PBS; and root dry weight of cotoneaster grown in 60% VC was greater than PBS (Table 6). Verbena root, vegetative top, and flower bud dry weight were unaffected by VC rate (Table 7). However, root, vegetative top, and flower bud dry weights of verbena grown in 20% VC were greater than PBS (Table 7). Cotoneaster RTR increased and verbena RTR decreased with increasing VC rate. Both cotoneaster and verbena top dry weight grown in 0% VC were less than plants grown in PBS which is not surprising as no limestone or micronutrients were added to this treatment (Tables 6 and 7). These results are in agreement with those reported by Atiyeh et al. (2002) and Hidalgo and Harkess (2002a, 2002b) in which top dry weight of greenhouse grown marigold, chrysanthemum, and poinsettia crop increased with increasing VC rates ranging from 0% VC to 100% VC in a PM substrate.

In contrast, gardenia root and top dry weights and top dry weight of coreopsis decreased linearly with increasing VC rate (Tables 8 and 9). Root and top dry weights of gardenia grown in ≤ 20% VC were equivalent to PBS, whereas gardenia root and top dry weights at ≥ 40% VC were less than PBS (Table 8). Coreopsis top dry weight grown in 10%, 20%, and 40% VC was equivalent to PBS, whereas top dry weight of coreopsis grown in 0% and 60% VC were less than PBS (Table 9). Interveinal chlorosis characteristic of Fe deficiency on new foliage of gardenia was observed when grown in 60% VC. Thus, the decreased growth may be due to Fe deficiency resulting from the elevated substrate solution pH associated with higher rates of VC.

Water use efficiency. Cotoneaster WUE_p was unaffected by VC rate (mean = 432 $ml \cdot g^{-1}$ ± 16, n=16) (data not presented). In addition, there were no difference of WUE_p between ≥ 10% VC rates and PBS (mean = 442 $ml \cdot g^{-1}$ ± 12.8, n=20), however, WUE_p of each of these five treatments improved compared to 0% VC (mean = 589 $ml \cdot g^{-1}$ ± 8, n=4). Verbena WUE_p was also unaffected by VC rate (mean = 587 $ml \cdot g^{-1}$ ± 357, n=16). However, verbena WUE_p of 20% VC (mean = 475 $ml \cdot g^{-1}$ ± 19, n=4) was improved compared to PBS (mean = 630 $ml \cdot g^{-1}$

± 62, n=4); and 20% VC and PBS was improved compared to 0% VC (mean = 777 $ml \cdot g^{-1}$ ± 46) (Table 7).

Mineral nutrient concentration. Cotoneaster top N, Ca, Mg, Fe, Cu, and B concentrations were unaffected by rates of VC (Tables 10 and 11). In contrast, top P, K, S, Mn, Zn, and Na concentration of cotoneaster decreased linearly with increasing rates of VC (Tables 10 and 11). Verbena top mineral nutrient concentrations had similar trends as cotoneaster for N, K, Mg, Fe, Cu, Mn, and Zn; however verbena top P, S, and Na concentrations were unaffected by VC rate, and verbena top Ca and B concentrations increased with increased rates of VC (Tables 12 and 13). Likewise, response of top nutrient concentrations of gardenia to VC were similar to cotoneaster and verbena, except K, which was unaffected by VC rate (data not presented).

With few exceptions, cotoneaster top N, K, Fe, Zn, and Cu concentrations grown in VC rates ≥ 10% were equivalent to PBS, cotoneaster top P, Ca, and B concentration for VC rates ≥ 10% were greater than PBS, and cotoneaster top Mg, Mn, and Na concentrations for VC rates ≥ 10% were less than PBS (Tables 10 and 11). Generally, verbena top P, Mg, S, and Zn concentrations grown in VC rates ≥ 10% were the same as PBS, verbena top Ca concentrations for VC rates ≥ 10% were greater than PBS, and verbena top N, K, Fe, Mn, and Cu concentrations for VC rates ≥ 10% were less than PBS (Tables 12 and 13). The differences in nutrient concentration between species may be due to different CRF formulation provided, species, and/or length of growing period.

Pn and gs. P_n (mean = 15.7 $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$ ± 0.4), g_s (mean = 0.29 $mol\ H_2O \cdot m^{-2} \cdot s^{-1}$ ± 0.02), and WUE_{Pn} (mean = 0.018 $mol\ H_2O \cdot \mu mol^{-1}\ CO_2$ ± 0.007) of cotoneaster were unaffected by VC (data not presented). These results suggest that no treatments were undergoing water stress, as leaf Pn typically decreases due to water stress (Chaves et al., 2002). Likewise, no differences were detected for verbena P_n (mean = 12.8 µmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ ± 1.1 SE) or g_s (mean = 0.21 mol $H_2O \cdot m^{-2} \cdot s^{-1}$ ± 0.02), however, WUE_{Pn} followed a quadratic model which yielded the best WUE_{Pn} at 42% VC (Table 14).

Although plant response varied by species, we conclude that 20% VC amended PB compared to PBS resulted in improved CC and AW at 53 DAI; greater cotoneaster top dry weight; greater verbena root, flower bud, and vegetative top dry weight; and improved WUE_P of verbena. Additionally, 20% VC resulted in equivalent gardenia dry top and root dry weight; equal coreopsis top dry weight; and equal WUE_P cotoneaster compared to PBS. Furthermore, 20% VC provided adequate liming equivalencies, thus precluding the need to amend the substrate with dolomitic limestone.

Literature Cited

Atiyeh, R.M., N.Q. Arancon, C.A. Edwards, and J.D. Metzger. 2002. The influence of earthworm-processed pig manure on the growth and productivity of marigolds. Bioresource Technol. 81:103-108.

Atiyeh, R.M., S. Subler, C.A. Edwards, G. Bachman, J.D. Metzger, W. Shuster. 2000. Effects of vermicomposts and composts on plant growth in horticultural container media and soil. Pedobiologia 44:579-590.

Bailey, D., T. Bilderback, and D. Bir. 1999. Water considerations for container production of plants. N.C. Coop. Ext. Serv. Hort. Info. Lflt 557.

Bilderback, T.E., S.L. Warren, J.S. Owen, Jr., and J.P. Albano. 2005. Healthy substrates need physicals too! HortTechnology. 15:747-751.

Campbell, C.R. 1992. Determination of total nitrogen in plant tissue by combustion. p. 21-23. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Campbell, C.R. and C.O. Plank. 1992. Sample preparation. p. 8-9. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Chaves, M.M., J.S. Pereira, J. Maroco, M.L. Rodrigues, C.P.P Ricardo, M.L. Osorio, I. Carvalho, T. Faria, and C. Pinheiro. 2002. How plants cope with water stress in the field. Photosynthesis and growth. Ann. Bot. 89:907-916.

Donohue, S.J. and D.W. Aho. 1992. Determination of P, K, Ca, Mg, Mn, Fe. Al, B, Cu, and Zn in plant tissue by inductively coupled plasma (ICP) emission spectroscopy. p. 37-40. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Eastman, B.R., P.N. Kane, C.A. Edwards. L. Trytek, B. Gunadi, A.L. Sterner, and J.R. Mobley. 2001. The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. Compost Sci. Util. 9:38-49.

Edwards, C.A. June 1995. Historical overview of vermicomposting. BioCycle 36:50-54.

Handreck, K. and N. Black. 2002. Growing media for ornamental plants and turf. 3rd ed. NSW Press, Sydney.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertility: an introduction to nutrient management. 7th ed. Prentice Hall, N.J.

Hidalgo, P.R. and R.L. Harkess. 2002a. Earthworm castings as a substrate amendment for chrysanthemum production. HortScience 37:1035-1039.

Hidalgo, P.R. and R.L. Harkess. 2002b. Earthworm castings as a substrate amendment for poinsettia production. HortScience 37:304-308.

Hidalgo, P.R., F.B. Matta, and R.L. Harkess. 2006. Physical and chemical properties of substrates containing earthworm castings and effects on marigold growth. HortScience 41:1474-1476.

Jackson, B.E., A.N. Wright, D.M. Cole, and J.F Sibley. 2005. Cotton gin compost as a substrate component in container production of nursery crops. J. Environ. Hort. 23:118-122.

Marini, R.P. 1999. Are nonsignificant differences really not significant? HortScience 34:761-762.

McGinnis, M.S. 2007. Sustainable use of vermicomposted hog waste: The use of worm castings as nursery growing substrates amendment to increase water and nutrient efficiency in containerized nursery plant production. North Carolina State Univ., Raleigh, PhD Diss.

Mehlich, A., S.S. Bowling, and A.L. Hatfield. 1976. Buffer pH acidity in relation to nature of soil acidity and expression of lime requirement. Commun. Soil Sci. Plant Anal. 7(3)25363.

Mokolobate, M.S., and R.J. Haynes. 2002. Comparative liming effect of four organic residues applied to an acidic soil. Biol. Fert. Soil. 35:79-85.

Paul, L.C. and J.D. Metzer. 2005. Impact of vermicompost on vegetable transplant quality. HortScience 40:2020-2023.

Tyler, H.H., S.L. Warren, T.E. Bilderback, and W.C. Fonteno. 1993. Composted turkey litter: I. Effect on chemical and physical properties of a pine bark substrate. J. Environ. Hort. 11:131-136.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227-229.

Table 1. Initial chemical properties of substrate components.

Substrate component[z]	N	P	K	Ca	Mg	S	C	CEC[y]
	mg·g^{-1}							meq·100 cm^{3}
VC	17.4[x] ± 0.4	15.9 ± 0.7	1.4 ± 0.0	79.7 ± 1.9	2.8 ± 0.1	2.9 ± 0.1	228 ± 10	89 ± 6.0
PB	3.5 ± 0.4	0.3 ± 0.1	1.1 ± 0.2	3.9 ± 0.4	0.6 ± 0.1	0.5 ± 0.1	555 ± 11	12 ± 0.3

Substrate component	Fe	Mn	Zn	Cu	B	Na	EC	pH
	µg·g^{-1}						dS·m^{-1}	
VC	2825 ± 70	633 ± 21	413 ± 15	94 ± 4	18 ± 1	546 ± 29	4.16 ± 0.41	6.03 ± 0.08
PB	1442 ± 149	62 ± 10	34 ± 6	5 ± 1	8 ± 2	313 ± 24	0.23 ± 0.00	3.79 ± 0.11

[z]VC = Vermicompost derived from hog manure; PB = pine bark.

[y]CEC = Cation exchange capacity.

[x]Means and ± 1 SE for VC based on 22 observations; means and ± 1 SE for PB based on four observations; means and ± 1SE for CEC based on three observations for VC and PB.

Table 2. Physical properties of vermicompost (VC) amended pine bark substrates 53 days after initiation.

VC rate (v/v)	Total porosity[z]	Air space[y]	Container capacity[x]	Available water[w]	Unavailable water[v]	Bulk density[u] (D_b)
	Percent volume					$g \cdot cc^{-1}$
0%	84* ± 1.0[t]	32* ± 1.1	52 ± 1.4	21* ± 1.4	31* ± 0.6	0.18*
10%	88* ± 0.8	30 ± 0.5	58 ± 0.8	30 ± 0.8	28* ± 0.9	0.18*
20%	90* ± 0.5	32* ± 1.4	59* ± 1.4	32* ± 1.4	26 ± 0.5	0.18*
40%	90* ± 0.7	30 ± 1.9	60* ± 1.6	30 ± 1.6	30* ± 0.5	0.20*
60%	89* ± 0.5	28 ± 1.7	61* ± 2.1	33* ± 2.1	28* ± 0.9	0.21*
PBS[s]	82 ± 0.3	27 ± 1.8	54 ± 1.6	28 ± 1.6	26 ± 0.6	0.30
Target range[r]	50-85	10-30	45-65	25-35	25-35	0.19-0.27
Regression[q]						
Linear	0.011	0.054	0.002	0.004	0.351	<0.001
Quadratic	0.001	0.642	0.105	0.049	0.087	0.359

[z]Based upon percent volume air and water of a 7.6 x 7.6 cm core at 0 kPa.

[y]Measured as percent volume air of a 7.6 x 7.6 cm core at 0 kPa.

[x]Measured as percent volume water of a 7.6 x 7.6 cm core after drainage at 0 kPa.

[w]Calculated by container capacity - unavailable water.

[v]Based upon percent volume water retained of a 2.2 x 7.6 cm core at 1500 kPa.

[u]All SE of bulk density were <0.008

[t]Each mean ± 1 SE based on five observations.

[s]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[r]Yeager et al., 1997

[q]PBS not included in regression analysis; 0% VC included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 3. Physical properties of vermicompost (VC) amended pine bark substrates 164 days after initiation.

VC rate (v/v)	Total porosity[z]	Air space[y]	Container capacity[x]	Available water[w]	Unavailable water[v]	Bulk density[u]
	Percent volume					$g \cdot cc^{-1}$
0%	84 ± 2.5[t]	32 ± 3.2	52 ± 1.9	19 ± 1.9	34* ± 0.8	0.20*
10%	84 ± 1.6	34* ± 1.2	50 ± 2.4	20 ± 2.4	30 ± 0.8	0.21*
20%	85* ± 1.7	32 ± 1.2	53 ± 2.6	21 ± 2.6	32* ± 1.6	0.19*
40%	88* ± 1.6	30 ± 1.3	58* ± 2.4	28 ± 2.4	30 ± 0.3	0.21*
60%	87* ± 3.3	28 ± 1.0	59* ± 3.5	28 ± 3.5	31* ± 0.6	0.23*
PBS[s]	79 ± 1.3	28 ± 2.0	51 ± 1.8	22 ± 1.8	29 ± 0.3	0.34
Target range[r]	50-85	10-30	45-65	25-35	25-35	0.19-0.27
Regression[q]						
Linear	0.151	0.031	0.013	0.004	0.165	0.260
Quadratic	0.741	0.485	0.842	0.712	0.177	0.503

[z]Based upon percent volume air and water of a 7.6 x 7.6 cm core at 0 kPa.

[y]Measured as percent volume air of a 7.6 x 7.6 cm core at 0 kPa.

[x]Measured as percent volume water of a 7.6 x 7.6 cm core after drainage at 0 kPa.

[w]Calculated by container capacity - unavailable water.

[v]Based upon percent volume water retained of a 2.2 x 7.6 cm core at 1500 kPa.

[u]All SE of bulk density were <0.002

[t]Each mean ± 1 SE based on five observations.

[s]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[r]Yeager et al., 1997

[q]PBS not included in regression analysis; 0% VC included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 4. Effect of vermicompost (VC) amended pine bark substrate on cotoneaster substrate solution pH.

VC rate (v/v)	pH						
	Days after planting						
	2	14	28	42	56	79	98
0%	4.7* ± 0.0[z]	4.0* ± 0.1	4.3* ± 0.1	4.2* ± 0.0	4.0* ± 0.1	3.7* ± 0.1	3.6* ± 0.2
10%	5.9 ± 0.2	5.8* ± 0.1	6.1* ± 0.3	6.0* ± 0.1	6.0* ± 0.1	5.0 ± 0.1	5.0 ± 0.3
20%	6.5* ± 0.1	6.7* ± 0.1	6.8* ± 0.1	7.0* ± 0.0	6.5* ± 0.1	5.9 ± 0.2	5.6* ± 0.2
40%	6.8* ± 0.1	7.1* ± 0.0	7.3* ± 0.0	7.3* ± 0.1	7.1* ± 0.1	6.3* ± 0.3	6.2* ± 0.3
60%	6.8* ± 0.0	7.1* ± 0.1	7.3* ± 0.0	7.4* ± 0.1	6.9* ± 0.1	6.3* ± 0.2	6.1* ± 0.2
PBS[y]	5.9 ± 0.1	5.4 ± 0.1	5.6 ± 0.1	5.5 ± 0.1	5.4 ± 0.1	5.5 ± 0.2	4.7 ± 0.1
Significance[x]							
Quad. plat.	0.025	0.024	0.033	0.021	0.059	0.008	0.027

[z]Each mean ± 1 SE based on four observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[x]Quad plat. = quadratic plateau. P values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at P=0.10.

The quadratic plateau equations are as follows: DAP 2, if $x < 30$, then pH = $-0.002x^2 + 0.14x + 4.7$, R^2 = 0.97, if $x \geq 30$, then pH = 6.8; DAP 14, if $x < 30$, then pH = $-0.003x^2 + 0.21x + 4.1$, R^2 = 0.98, if $x \geq 30$, then pH = 7.1; DAP 28, if $x < 29$, then pH = $-0.003x^2 + 0.20x + 4.3$, R^2 = 0.97, if $x \geq 29$, then pH = 7.2; DAP 42, if $x < 29$, then pH = $-0.004x^2 + 0.22x + 4.7$, R^2 = 0.98, if $x \geq 29$, then pH = 7.3; DAP 56, if $x < 27$, then pH = $-0.004x^2 + 0.21x + 4.0$, R^2 = 0.94, if $x \geq 27$, then pH = 6.9; DAP 79, if $x < 34$, then pH = $-0.002x^2 + 0.16x + 3.7$, R^2 = 0.99, if $x \geq 34$, then pH = 6.3; DAP 98, if $x < 35$, then pH = $-0.002x^2 + 0.14x + 3.7$, R^2 = 0.97, if $x \geq 35$, then pH = 6.1.

Table 5. Effect of vermicompost (VC) amended pine bark substrate on cotoneaster substrate solution electrical conductivity (EC).

VC rate (v/v)	EC ($dS \cdot m^{-1}$)						
	Days after planting						
	2	14	28	42	56	79	98
0%	0.2 ± 0.0[z]	1.1 ± 0.2	0.5 ± 0.0	0.7 ± 0.0	0.7 ± 0.0	0.6 ± 0.1	0.4 ± 0.0
10%	0.9 ± 0.2	0.8 ± 0.1	0.8 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	0.3 ± 0.1
20%	1.4* ± 0.5	1.0 ± 0.1	0.8 ± 0.1	0.5 ± 0.0	0.6 ± 0.1	0.5 ± 0.0	0.3 ± 0.0
40%	1.9* ± 0.5	0.9 ± 0.1	0.8 ± 0.1	0.6 ± 0.0	0.5 ± 0.1	0.6 ± 0.1	0.4 ± 0.0
60%	2.5* ± 0.1	1.4* ± 0.2	1.1* ± 0.2	0.9* ± 0.1	0.8 ± 0.2	0.7 ± 0.1	0.6* ± 0.1
PBS[y]	0.6 ± 0.0	0.9 ± 0.1	0.8 ± 0.2	0.5 ± 0.1	0.6 ± 0.2	0.6 ± 0.1	0.3 ± 0.0
Regression[x]							
Linear	<0.001	0.209	0.007	0.029	0.276	0.652	0.019
Quadratic	0.376	0.070	0.897	0.004	0.041	0.402	0.172

[z]Each mean ± 1 SE based on four observations..

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[x]PBS not included in regression analysis; 0% VC included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 6. Root, top, and total dry weight; and root to top ratio (RTR) of *Cotoneaster dammeri* 'Skogholm' grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	Root dry weight	Top dry weight[z]	RTR[z]
	g		$g \cdot g^{-1}$
0%	13.5 ± 1.2[y]	64* ± 2	0.21* ± 0.02
10%	14.2 ± 0.4	112 ± 3	0.13 ± 0.00
20%	15.2 ± 1.4	118* ± 6	0.13 ± 0.01
40%	16.1 ± 0.4	125* ± 3	0.13 ± 0.00
60%	18.7* ± 0.6	126* ± 2	0.15 ± 0.01
PBS[x]	14.6 ± 0.8	108 ± 1	0.14 ± 0.01
Regression[w]			
Linear	0.001	0.010	0.013

[z-]Top dry weight = stem + leaf dry weights; total dry weight = root + top dry weights; RTR (root to top ratio) = root weight (g) ÷ top dry weight..

[y]Each mean ± 1 SE based on 4 observations.

[x]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[w]PBS and 0% VC not included in regression analysis.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at P=0.10.

The linear equations are as follows: root dry weight (y = 0.08x + 13, R^2 = 0.96), top dry weight (y = 0.28x + 111, R^2 = 0.87), total dry weight (y = 0.37x + 124, R^2 = 0.94), and RTR (y = 0.0003x + 0.11, R^2 = 0.74).

Table 7. Root, vegetative top, and flower bud dry weights, root weight ratio, and water use efficiency of *Verbena canadensis* 'Purple Homestead' grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	Root dry weight	Vegetative top dry weight	Bud dry weight	RTR[z]	WUE_p[y]
		g			
0%	2.8 ± 0.2[x]	9.8* ± 0.7	0.6 ± 0.1	0.29* ± 0.01	777* ± 46
10%	4.8* ± 0.6	20.0 ± 2.4	2.5* ± 0.9	0.24 ± 0.02	636 ± 65
20%	4.7* ± 0.3	21.0* ± 2.1	2.7* ± 0.4	0.23 ± 0.03	475* ± 19
40%	4.0 ± 0.4	19.7 ± 1.8	1.9 ± 0.2	0.20 ± 0.01	577 ± 90
60%	3.9 ± 0.7	19.2 ± 1.8	1.7 ± 0.7	0.20 ± 0.02	662 ± 78
PBS[w]	3.5 ± 0.2	15.9 ± 0.8	1.2 ± 0.5	0.22 ± 0.02	630 ± 62
Regression[v]					
Linear	0.116	0.625	0.190	0.068	0.430

[z]RTR (root to top ratio) = root weight (g) ÷ top dry weight.

[y]WUE_p (water use efficiency of productivity) = total irrigation water retained (mL) ÷ total dry weight (g).

[x]Each mean ± 1 SE based on 4 observations.

[w]PBS= 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[v]PBS and 0% VC not included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 8. Root and top dry weight of *Gardenia jasminoides* 'Chuck Hayes' grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	Root dry weight	Top dry weight
	g	
0%	11.8 ± 1.8[z]	42.8 ± 4.3
10%	11.5 ± 1.0	47.3 ± 4.4
20%	10.0 ± 0.9	44.8 ± 1.4
40%	8.9 ± 1.6	35.1* ± 6.3
60%	5.7* ± 0.9	23.6* ± 3.7
PBS[x]	11.8 ± 1.2	50.8 ± 3.2
<u>Regression</u>[w]		
Linear	0.002	<0.001

[z]Each mean ± 1 SE based on 4 observations.

[x]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg\cdot m^{-3}$ dolomitic limestone.

[w]PBS and 0% VC not included in regression analysis. P values listed.

*Significantly different from PBS substrate based on single degree of freedom contrast tests at P=0.10.

The linear equations are as follows: root dry weight (y = -0.11x + 12.5, R^2 = 0.96) and top dry weight (y = -0.59x + 66, R^2 = 0.99).

Table 9. Top dry weight of *Coreopsis* grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	Top dry weight g
0%	12.2* ± 1.1[z]
10%	21.7 ± 3.7
20%	17.0 ± 2.2
40%	13.1 ± 1.4
60%	7.7* ± 2.2
PBS[w]	14.9 ± 1.6
Regression[v]	
Linear	<0.001

[z]Each mean ± 1 SE based on 4 observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg{\cdot}m^{-3}$ dolomitic limestone.

[x]PBS and 0% VC not included in regression analysis.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at P=0.10.

The linear equation is as follows: top dry weight, $y = -0.26x + 23$, $R^2 = 0.98$.

Table 10. Macro mineral nutrient top concentration of *Cotoneaster dammeri* 'Skogholm' grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	N	P	K	Ca	Mg	S
	$mg \cdot g^{-1}$					
0%	17.8* ± 1.4[z]	1.6* ± 0.1	12.1* ± 0.7	5.2* ± 0.3	2.1* ± 0.1	2.0* ± 0.3
10%	11.0 ± 1.5	2.6* ± 0.1	10.7 ± 0.2	13.0* ± 0.9	2.3* ± 0.1	1.4 ± 0.1
20%	11.3 ± 1.2	2.6* ± 0.1	10.4 ± 0.4	13.9* ± 0.5	2.3* ± 0.1	1.2 ± 0.1
40%	11.5 ± 1.0	2.4* ± 0.1	10.1 ± 0.3	14.7* ± 0.3	2.3* ± 0.1	0.9* ± 0.0
60%	11.1 ± 1.0	2.3* ± 0.1	9.9 ± 0.3	14.5* ± 0.6	2.4* ± 0.1	0.8* ± 0.1
PBS[y]	11.7 ± 0.5	1.1 ± 0.0	10.0 ± 0.3	6.6 ± 0.2	2.7 ± 0.1	1.3 ± 0.1
<u>Regression</u>[x]						
Linear	0.932	0.051	0.053	0.102	0.302	<0.001

[z]Each mean ± 1 SE based on 4 observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[x]PBS and 0% VC not included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 11. Micro mineral nutrient top concentration of *Cotoneaster dammeri* 'Skogholm' grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	Fe	Mn	Zn	Cu	B	Na
	ug·g^{-1}					
0%	55.8 ± 3.6	310* ± 48	109* ± 11	6.5 ± 0.6	42.0 ± 4.3	1397* ± 88
10%	59.1 ± 5.2	204 ± 14	68 ± 4	6.1 ± 0.6	51.5* ± 1.9	1518* ± 118
20%	52.7 ± 2.7	174* ± 14	58 ± 4	6.7 ± 0.5	51.9* ± 2.2	1205* ± 33
40%	48.2* ± 1.4	106* ± 7	56 ± 3	6.6 ± 0.4	53.3* ± 1.1	1037* ± 37
60%	52.1 ± 5.4	53* ± 7	45* ± 5	5.9 ± 0.3	52.3* ± 1.8	820* ± 58
PBS[y]	59.6 ± 5.5	229 ± 9	66 ± 1	6.3 ± 0.4	39.3 ± 1.9	1768 ± 58
Regression[x]						
Linear	0.228	<0.001	0.001	0.657	0.639	<0.001

[z]Each mean ± 1 SE based on 4 observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 kg·m^{-3} dolomitic limestone.

[x]PBS and 0% VC not included in regression analysis. *P* values listed.

*Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 12. Macro mineral nutrient top concentration of *Verbena canadensis* 'Purple Homestead'grown in vermicompost (VC) amended pine bark.

VC rate	N	P	K	Ca	Mg	S
(v/v)	$mg\cdot g^{-1}$					
0%	38.9* ± 0.7	3.8 ± 0.2	21.7* ± 1.4	4.3* ± 0.2	3.9* ± 0.2	2.7 ± 0.0
10%	22.4* ± 1.0	4.0* ± 0.1	23.5* ± 0.9	13.5* ± 0.6	5.3 ± 0.2	2.5 ± 0.1
20%	22.9* ± 0.8	3.8 ± 0.2	21.3* ± 0.9	14.4* ± 0.8	5.2 ± 0.3	2.5 ± 0.2
40%	21.9* ± 1.1	3.9 ± 0.1	20.0* ± 0.6	19.8* ± 1.6	5.4 ± 0.3	2.7 ± 0.2
60%	22.5* ± 1.0	3.7 ± 0.2	16.8* ± 0.7	21.9* ± 1.5	5.4 ± 0.3	2.7 ± 0.2
PBS[y]	28.9 ± 1.0	3.5 ± 0.2	26.9 ± 1.3	6.3 ± 0.4	5.3 ± 0.4	2.7 ± 0.1
Regression[x]						
Linear	0.877	0.387	<0.001	<0.001	0.597	0.251

[z]Each mean ± 1 SE based on 4 observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg\cdot m^{-3}$ dolomitic limestone.

[x]PBS and 0% VC not included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 13. Micro mineral nutrient top concentration of *Verbena canadensis* 'Purple Homestead'grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	Fe	Mn	Zn	Cu	B	Na
	$ug \cdot g^{-1}$					
0%	114* ± 5	322* ± 41	85* ± 9.1	12* ± 1.2	30* ± 0.7	530* ± 23
10%	112* ± 4	158* ± 10	68 ± 4.3	14 ± 1.0	36 ± 1.6	505* ± 20
20%	107* ± 6	131* ± 17	69 ± 5.5	9* ± 1.0	35 ± 0.6	463* ± 41
40%	121 ± 7	67* ± 8	52 ± 3.5	13* ± 0.9	39* ± 1.9	497* ± 33
60%	111* ± 8	64* ± 5	53 ± 6.1	11* ± 1.5	40* ± 1.4	502* ± 32
PBS[y]	136 ± 10	261 ± 22	63 ± 3.3	17 ± 1.5	34 ± 2.2	600 ± 35
Regression[x]						
Linear	0.659	<0.001	0.014	0.509	0.023	0.761

[z]Each mean ± 1 SE based on 4 observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[x]PBS and 0% VC not included in regression analysis. *P* values listed.

[*]Significantly different from PBS substrate based on single degree of freedom contrast tests at *P*=0.10.

Table 14. Water use efficiency of photosynthesis (WUE_{Pn}) of *Verbena canadensis* 'Purple Homestead' grown in vermicompost (VC) amended pine bark.

VC rate (v/v)	WUE_{Pn} mol $H_2O \cdot \mu mol^{-1}$ CO_2
0%	0.013 ± 0.002[z]
10%	0.015 ± 0.002
20%	0.014 ± 0.001
40%	0.018 ± 0.002
60%	0.021* ± 0.004
PBS[y]	0.015 ± 0.002
Regression[x]	
Linear	0.054
Quadratic	0.007

[z]Each mean ± 1 SE based on 4 observations.

[y]PBS = 8 pine bark : 1 sand (v/v) with 1.8 $kg \cdot m^{-3}$ dolomitic limestone.

[x]PBS and 0% VC not included in regression analysis. *P* values listed.

*Significantly different from PBS substrate based on single degree of freedom contrast tests at P=0.10.

The equation is as follows WUE_{Pn}, $y = 0.00006x^2 + 0.00005x + 0.015$; $R^2 = 0.96$.

Chapter 3

Nutrient contribution and release kinetics of vermicompost amended pine bark

(In the format appropriate for submission to Compost Science and Utilization)

Compost Science and Utilization

Nutrient contribution and release kinetics of vermicompost amended pine bark

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Abstract

Vermicompost (VC) amended to soilless substrates for containerized crop production may provide plant available nutrients, thus allowing the reduction/elimination of fertilizer nutrient inputs. The objectives of this study were to quantify macronutrient content released into solution on a volume basis and to describe the nutrient release kinetics of various rates of VC amended pine bark. Five VC amended PB substrate treatments, 0, 10, 20, 30, and 40%

VC (v/v), were packed into a 690 cm^3 PVC column (length = 30.5 cm, diameter = 5.1 cm), sealed with endcaps drilled with a 5-mm hole to allow for gas exchange, and placed in a 25°C incubation chamber. At weeks 0, 1, 2, 4, 6, 8, 10, 12, 14, and 16, columns were leached with 0.01M KCl. Leachate was collected and submitted to NCDA&CS for analysis of IN-N (as NH_4-N and NO_3-N) and total P, Ca, Mg, S, and pH. Cumulative nutrient contents released into substrate solution were transformed to 4-L basis (mg/4 L), for easy application of results to containerized crop production. Additionally cumulative nutrient released as a percent of initial nutrient was calculated and used to determine the release rate. As VC rate increased, substrate solution pH increased linearly before reaching a plateau at pH 6.1 corresponding to 25 to 29% VC. As VC rate increased, cumulative IN-N, Ca, Mg, and S content released into the substrate solution increased linearly and cumulative P decreased quadratically at all time points. For each 10% increase of VC, the linear models predict an additional 115 mg N, 188 mg Ca, 31 mg Mg, and 19 mg S released into substrate solution at week 8 and an additional 207 mg N, 261 mg Ca, 43 mg Mg, and 30 mg S released into substrate solution at week 16. At weeks 8 and 16, P released into substrate solution was minimized at 36% VC. Release of nitrogen and sulfur followed a first-order model, calcium and magnesium followed a two-pool first/zero order model, and phosphorus followed a linear model. With the exception of N at 10%, the models calculated continued release of these nutrients beyond week 16.

Introduction

Vermicompost (VC) is produced when earthworms and bacteria stabilize organic waste through an aerobic, non-thermophillic process (Edwards 1995). Vermicompost is a proven technology for managing animal waste and has been shown to eliminate pathogens to United States Environmental Protection Agency Class A stabilization (Eastman *et al*. 2001; Edwards, 1995). Benefits of using VC as a soilless substrate amendment for container grown horticultural crops has been reported for a variety of reasons, including increased plant growth and flowering (Hidalgo and Harkess 2002) and improved physical properties (Hidalgo *et al*. 2006). Vermicompost also provides some, but not all, essential plant nutrients to maximize containerized crop growth, thus an additional source of nutrients (i.e. fertilizer) is needed (Atiyeh *et al*. 2000a; Atiyeh *et al.* 2000b; Atiyeh *et al*. 1999). Best management practices would dictate that conventional nutrient inputs should be reduced and/or eliminated to offset nutrients provided by VC to lessen environmental impact while optimizing plant growth.

This study focused on the aspect of plant available nutrients supplied by vermicomposted swine waste for the production of containerized nursery crops. Horticultural nursery crops accounted for ~75% of the $12 billion greenhouse/nursery crop cash receipts in 2004 (USDA 2006), and the nursery industry has been identified as a potential market for the use of composted materials (Walker *et al.* 2006). The primary containerized nursery crop substrate in the southeastern United States is loblolly and slash pine (*Pinus taeda* L. and *P. elliottii* Engelm.) bark milled to 1.25 cm (Yeager *et al.* 2007). To optimize nursery crop nutrient uptake while reducing nutrient runoff, nursery crop best management practices (BMPs) recommends that primary macronutrients [nitrogen (N), phosphorus (P), and potassium (K)] should be applied as a controlled release fertilizer (CRF) (Yeager *et al.* 2007). Additionally, the substrate should be amended with dolomitic limestone and a micronutrient package (Yeager *et al.* 2007). Dolomitic limestone provides the secondary plant macronutrients calcium (Ca) and magnesium (Mg) and serves to neutralize the acidity of pine bark. A micronutrient package amendment provides sulfated micronutrients including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) as well as the secondary plant macronutrient sulfur (S) (Browder, *et al.* 2005). An alternative source of micronutrients recommended by the BMPs is a 10% or greater (by vol.) compost amendment to the substrate (Yeager *et al.* 2007). The nature of the waste product from which the composted material is derived will determine if sufficient S is provided for optimal plant growth and whether an additional S source is needed (Handreck, 1986).

Nutrient release experiments involving organic amendments can provide plant available nutrient information. Most mineralization and nutrient release rate studies of composted materials have been conducted to simulate application to field crops, where compost is applied to mineral soils in units of weight per area (i.e. $t \cdot ha^{-1}$ and $kg \cdot ha^{-1}$) or weight per weight (i.e. $g \cdot kg^{-1}$ and % w/w) (Gale *et al.* 2006; Hadas and Portnoy 1998; Hartz *et al.* 2000; Preush *et al.* 2002; Stewart *et al.* 1998; Tognetti *et al.*2005). Although these composted materials may be of benefit for nursery crop production, results of these studies are difficult to transfer to containerized horticultural crops, where soilless substrates are used and substrates are prepared on a volume basis. Quantification of macronutrients released by

VC on a volume basis over time will provide nurserymen with information they can apply to their nutrient management program to produce nursery crops according to BMPs.

The objectives of this study were to quantify macronutrient content released into solution and to describe the nutrient release kinetics of various rates of VC amended pine bark. To achieve these objectives, a laboratory study was conducted to determine cumulative macronutrient content released into the substrate solution from five rates of VC amended pine bark over 16 weeks. These results will tell "how much" nutrient content was released into substrate solution and provide models to predict "how long" those nutrients will be released.

Materials and Methods

Experimental design, substrate treatments, and experimental units

The study was a randomized complete block design with five treatments and four replications. The treatments included aged (>1 year) pine bark screened ≤ 12.7 mm (moisture content of 0.6 $g \cdot g^{-1}$) combined with vermicompost (VC) (Vermicycle Organics, Wilson, NC) derived from hog manure (moisture content of 0.45 $g \cdot g^{-1}$) at 0, 10, 20, 30, or 40% VC (v/v) [0, 17, 32, 45, and 56% (w/w) dry mass basis] with respective bulk densities (D_b) of 0.18, 0.19, 0.21, 0.23, and 0.25 $g \cdot cm^{-3}$ dry mass basis. This equates to VC loading rates of 0, 23, 47, 70, and 95 mg (dry mass basis) per experimental unit [polyvinyl chloride column (PVC)]; and 0.0, 3.8, 8.5, 14.6, and 22.8 mg total $N \cdot g$ pine $bark^{-1}$.

Mineral nutrient analysis of the substrate components was conducted by the N.C. Department of Agriculture and Consumer Services (NCDA&CS), Agronomic Division, Raleigh (Table 1). Prior to analysis, samples were dried at 65°C and ground (ED-5 Wiley

Mill; Thomas Scientific, Swedesboro, N.J.) to pass through a 20 mesh (1 mm) screen (Campbell and Plank 1992). Total carbon (C) and N concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500; CE Elantech Instruments, Milan, Italy) (Campbell 1992). Inorganic N (IN-N) was extracted from the waste using 0.1M H_2SO_4 (1g/25mL), partitioned into nitrate (NO_3) and ammonium (NH_4) by EPA Methods 353.1 and 351.2, respectively, and concentrations were determined using an auto-flow spectrophotometric analyzer (4001 San^{plus} Segmented Flow Analyzer, Skalar Instruments; Breda, The Netherlands). Organic N (Org-N) was calculated as the difference between total N and IN-N. Total P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Wellesley, Mass.), following open-vessel HNO_3 digestion in a microwave digestion system (CEM Corp.; Matthews, NC) (Donohue and Aho 1992). Electrical conductivity (EC) was determined using a 1 substrate : 2 distilled water extract (v/v), and pH was determined using a 1 substrate : 1 distilled water extract (v/v). Cation exchange capacity (CEC) was determined by summation of basic cations (excluding Na) and buffer acidity (Mehlich *et al.* 1976).

Substrates were placed in PVC (length = 30.5 cm, diameter = 5.1 cm) with each end sealed with a PVC cap (total volume with bottom end cap = 690 cm^3). A 5-mm hole was drilled in each end cap to allow for gas exchange. Columns were filled, tapped three times, and topped off to achieve a fresh D_b within ±0.006 $g\cdot cm^{-3}$ for each substrate. Deionized water was added to each column to achieve 100% container capacity (CC) as determined by gravimetric measures of a fifth replication specifically included only for gravimetric measurements. Container capacity is defined as the amount of water held in the substrate against the force of gravity. Following collection of week 0 substrate solution, columns were placed horizontally in an incubation chamber (D-7440, Lab-Tech, Inc., Crystal Lake, Ill.) at 25°C with a flooded chamber floor.

Substrate solution collection procedures

Substrate solution samples were collected by plugging the bottom end cap, placing the columns vertically, adding ~50 mL 0.01M KCl, and draining into collection containers. About 50 mL of substrate solution was collected and frozen immediately. Exact volumes collected were recorded so nutrient content in the substrate solution could be calculated. The volume of KCl added was calculated to maintain substrates at 100% CC. Based on gravimetric measurements, moisture loss during incubation was negligible. Substrate solution samples were collected at weeks 0, 1, 2, 4, 6, 8, 10, 12, 14, and 16. Chemical analysis was conducted by the NCDA for IN-N (as NH_4-N and NO_3-N) and total P, Ca, Mg, S, B, Cu, Fe, Mn, and Zn by methods described previously. Potassium levels in the substrate solution were not analyzed due to inputs of K in extracting solution. Substrate solution pH was determined (Orion, Model 920). Losses due to NH_3 volatilization were not measured, but were considered minimal under experimental conditions (Brady and Weil, 2002).

Equations and statistical analysis

The nutrient content (mg) released into the substrate solution within each column was determined by multiplying the nutrient concentration ($mg \cdot L^{-1}$) by the volume of substrate solution leached (L). Nutrient content (mg) released was multiplied by 5.80 to express data as mg nutrient released in substrate solution on a volume basis (mg/4 L). Units of nutrient content released per 4 L container (#1 nursery container) allows easy application of results from this study to containerized crop production. Cumulative nutrient content released was determined by summing nutrient content released by each column at successive time points. Nutrient content released at week 0 was not included in the cumulative nutrient content calculation, as nutrients released at week 0 represent nutrients that would be leached upon initial irrigation of potted plants and would not available for plant uptake. Hereafter, "cumulative nutrient content released" refers to the nutrient content released into the substrate solution on a 4 L basis (mg/4 L). Cumulative nutrient content released at each week of solution collection were analyzed using regression analysis with SAS version 9.1 (SAS Inst. Inc., Cary, NC).

The initial loading nutrient content (mg) on a 4 L basis for each substrate treatment provided by the VC is included in Table 2. The cumulative percent of initial nutrient content released into the substrate solution (referred to hereafter as "cumulative percent nutrient released") was calculated according to Eq. [1] where $(\%\ NUT_{rel})_{VC}(VC_t)$ is the cumulative percent of initial nutrient released from VC for VC treatment t (%), $(NUT_{rel})(VC_t)_{wk}$ is the nutrient content released by VC treatment t at week *w* (mg/4 L), $(NUT_{rel})(VC_{0\%})_w$ is the nutrient content released by the control treatment (0% VC) at week *w* (mg/4 L), and $(NUT_i)(VC_t)$ is the initial VC nutrient content or loading rate (mg/4 L).

[1] $(\%\ NUT_{rel})(VC_t) = \{\Sigma\ [(NUT_{rel})(VC_t)_{wk} - (NUT_{rel})(VC_{0\%})_{wk}\} / (NUT_i)(VC_t),$

Cumulative percent nutrient released data were analyzed with PROC NLIN (SAS version 9.1) to determine if the nutrient release rate model was first order, zero order, or first/zero order and to estimate the release rate parameters. First and zero order models designate nutrients to one pool, whereas a first/zero model designated nutrients to two pools (easily available and slowly available pool). If data could be described by more than one model, the model with the lowest mean square error was used. The first, zero, and first/zero order equations are shown as Eq. [2], [3], and [4], respectively, where % NUT_{rel} is the cumulative percentage of nutrient released (%), a is the potentially available/mineralizable/exchangeable nutrient pool (%), e is exponential constant (~ 2.718), k_1 is the first-order rate constant (wk^{-1}), k_0 is the zero-order rate constant (% nutrient/wk^{-1}), and t is time (week).

[2] % $NUT_{rel} = a\,[1 - e^{(-k1t)}]$

[3] % $NUT_{rel} = k_0 t$

[4] % $NUT_{rel} = a\,[1 - e^{(-k1t)}] + k_0 t$

Results and Discussion

Cumulative nutrient content released by pine bark

The C:N ratio (115 ± 12) of pine bark shown in Table 1 is above the stability threshold (100) typically used to indicate pine bark stability (Handreck and Black 2002). The following nutrient cumulative contents released into the substrate solution at week 16 were 15 mg/4 L IN-N, 5.1 mg/4 L P, 58 mg/4 L Ca, 23 mg/4 L Mg, 3 mg/4 L S, 367 ug/4 L

(Tables 3). Thus pine bark is fairly inactive, contributing few plant nutrients to the substrate solution.

Substrate solution pH

Substrate solution pH increased linearly with increasing VC rate at all time points (Table 4). At weeks 4, 6, 8, 12, and 16, the linear model reached a plateau at pH 6.1 corresponding to 25% to 29% VC. These models estimated a VC rate of 20% to 25% would achieve a target substrate solution pH range of 5.5 to 6.0 which is recommended for most nursery crops (Handreck and Black 2002). These data are in agreement with other researchers who have demonstrated that some composted materials can provide liming effects. Hidalgo *et al*. (2006) and McGinnis (2007) reported an increased substrate solution pH with increased rate of VC amended to pine bark. Additionally, Tyler *et al.* (1993) and Vendrame and Moore (2005) reported increased substrate solution pH with increased rate of thermophillic compost amended to pine bark and peat moss, respectively. The various mechanisms by which organic residues provide liming effects are outlined by Mokolobate and Haynes (2002), where the authors hypothesized liming effects provided by composted materials are due to proton consumption by humic substance functional groups.

Cumulative nutrient content released by VC amended pine bark

As VC rate increased, cumulative IN-N, Ca, Mg, and S content released into the substrate solution increased linearly at all time points (Table 3). Greater than 99% of IN-N released into substrate solution by all treatments was NO_3 (data not presented). For each 10% increase of VC, the linear models predict an additional 115 mg N, 188 mg Ca, 31 mg Mg, and 19 mg S released into substrate solution at week 8 and an additional 207 mg N, 261 mg Ca, 43 mg Mg, and 30 mg S released into substrate solution at week 16. Due to the relatively high solubility and subsequent mobility of N, Ca, Mg, and S through substrate solution, these data can be used to estimate availability of nutrients for plant uptake by mass flow and to adjust fertilizer inputs to offset nutrients provided by VC.

As VC rate increased, cumulative P decreased quadratically at all time points (Table 3). At weeks 8 and 16, P released into substrate solution was minimized at 36% VC. This counterintuitive result may be explained by chemical processes in which P retention increases as pH increases within a system. The increased sorption of Ca-P complexes and/or precipitates resulting from increasing pH and subsequent decreased availability of P in substrate solution has been reported by Siddique and Robinson (2003) and Robinson and Sharpley (1996). In contrast to nutrients primarily taken up by plants via mass flow, the concentration of P in substrate solution is not indicative of P available for plant uptake. The primarily mechanism of P uptake is by diffusion, where P desorption from the solid phase to solution phase is driven by concentration gradients caused by plant uptake (Havlin et al. 2005). Thus, the ability of the substrate to retain P should also serve to supply a continuous source of P available for plant uptake. Handreck (1986) and McGinnis (2007) have demonstrated 20% VC amended to peat moss and pine bark can provide sufficient plant available P for optimal plant growth without an additional P source.

Nutrient release rate characteristics of VC

Nitrogen. The release of N from all VC rates followed a first order model (Figure 1). At week 16, the first order equations predicted that 10, 20, 30, and 40% VC released a calculated cumulative 6.9, 8.5, 8.7, and 9.5%, respectively, of initial N content. These cumulative percentages equate to 95, 86, 55, and 76%, respectively, of the potentially available N released at week 16. Thus, the potentially available N provided by VC amended at 10% is practically exhausted by week 16, while total N release from 20, 30, and 40% VC appears to continue beyond week 16.

A first-order release of N from composted materials has also been reported by Gale *et al.* (2006) and Hadas and Portnoy (1994). Additionally, the cumulative 7 to 10% of initial N released from VC reported herein are fairly consistent with that reported for other mineralization studies of vermicomposted materials. At 16 weeks, Hadas and Portnoy (1994) reported 6 to 11% of total N released by vermicomposted dairy manure amended to a mineral soil at a rate of 2875 mg total N/4 L (the equivalent approximate total N loading rate of 12% VC of this study). Tognetti *et al.* (2005) reported < 5% total N released by vermicomposted municipal waste amended to a mineral soil at rates approximating 824 and 1677 mg total N/4 L (the equivalent approximate total N loading rates of 4 and 7% VC of this study).

Results herein were also similar to those reported for materials produced from thermophillic composting processes. After 16 weeks, Kraus *et al.* (2000) reported 6% of total N released from municipal compost amended to pine bark at a rate of 3684 mg total N/4 L (the equivalent total N loading rate of 15% VC of this study). Hartz *et al.* (2000) reported 12% total N released from composted feed lot manure amended to mineral soil at an approximate total N loading rate of 2214 mg total N/4 L (the equivalent approximate loading rate of 9% VC of this study) at week 18. Additionally, Gale *et al.* (2006) evaluated 20 composts derived from various sources and materials amended to a mineral soil at rates ranging from 178 to 802 kg total N·ha^{-1} (the equivalent approximate total N loading rate of

2.5% to 9% VC of this study) and reported an average of 7% of total N was release as plant available N.

Sulfur. Sulfur released from all VC rates followed a first order model (Figure 1). Cumulative percentages were 13.2, 11.8, 8.8, and 8.7% of initial S content released into substrate solution at week 16, for the 10, 20, 30, and 40% VC rates, respectively. These S release percentages represent 74, 86, 84, and 80% of potentially available S, respectively, indicating all VC rates will release S into substrate solution beyond week 16. The first-order release rate of S from a composted material has also been reported by Stewart *et al.* (1998). They investigated the S release rate of spent mushroom compost amended to a mineral sandy loam soil at 20, 40, and 80 $t \cdot ha^{-1}$ soil (dry mass basis) with an approximate total N input rates equivalent to of 586, 1171, and 2342 mg total N/4 L (the ~ equivalent total N loading rate of 2, 5, and 10% VC of this study). A calculated 8% of total initial S was released at 16 weeks from all three spent mushroom compost rates.

Calcium and magnesium. The release of Ca and Mg from all VC rates was best described by a first/zero order two pool model, where the more readily decomposable pool was described by a first order equation and the relatively recalcitrant pool was represented by a zero order equation. At week 16, 2.5, 2.8 , 2.7, and 2.4% of initial Ca content; and 12.9, 13.6, 12.2, and 11.6% of initial Mg content, had been released into substrate solution for the 10, 20, 30, and 40% VC rates, respectively. These models for Ca and Mg also indicate that the two nutrients will be released into the substrate solution beyond week 16. Stewart *et al.* (1998) described release rates of Ca and Mg from spent mushroom compost by a first/zero order two pool model. A calculated 0.14 to 0.18% of total initial Ca was released and 0.42 to

0.58% of the total initial Mg was released for spent mushroom compost rates ranging from 20 to 80 t·ha^{-1}. The lower percentages of Ca and Mg released reported by Stewart et al. (1988), compared to data herein, may be due to the relatively lower Ca and Mg input rates of spent mushroom compost compared to VC and/or the nature of the substrate to which the compost was amended. A sandy loam mineral would have higher CEC compared to pine bark and thus would be able to retain a higher percentage of cations.

Phosphorus. The release of P from all VC rates followed a zero order model (Figure 3). At week 16, the zero order equation estimated VC rates of 10, 20, 30, and 40% released a cumulative 4, 1, 0.3, and 0.2% of the initial P content, respectively, into the substrate solution (Figure 2). Nair *et al.* (2003) reported P released from several sources and ages of dairy manure was released following a linear model.

Conclusions

The vermicomposted hog manure used with this study provided linear increase of the soluble nutrients N, Ca, Mg, and S into substrate solution with increasing rates of VC. Additionally, these nutrients were continuously released into substrate solution according to a first-order model (N and S) or a two-pool first/zero order model (Ca and Mg). With the exception of N at 10% VC, all nutrients were predicted to continue supplying the substrate solution beyond 16 weeks. In contrast, the relatively insoluble nutrient phosphorus was released into substrate solution according to a decreasing quadratic model with increasing VC rate. We hypothesize the increased pH associated with the higher VC rates increased P sorption to the solid phase resulting in lower content in the liquid phase. The release rate of P into the substrate solution followed a zero-order model.

In summary, the content of plant available N, Ca, Mg, and S in solution can be predicted, as these nutrients are water soluble and primary mode of plant uptake is by mass flow. In contrast, P has low relatively solubility, and P content released into solution is controlled by chemical properties, such as pH and concentration of P in solution. Thus, these models do not predict P content released into substrate solution, but can be useful predicting the ability of a substrate to retain P. Substrate retention can serve as a slow release source of P and may be able to minimizing leaching of P.

Acknowledgements

This research was funded in part by the North Carolina Agricultural Research Service (NCARS), Raleigh, NC 27695-7643 and the Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Fellowship. Use of trade names in this publication does not imply endorsement by the NCARS or EPA of products named nor criticism of similar ones not mentioned. Appreciation is extended to William M. Reece and Mary Lorscheider for technical assistance and Cavelle Brownie for statistical assistance. From a thesis submitted by M.S.M. in partial fulfillment of the requirements for the PhD degree.

References

USEPA, 1983. Nitrate-Nitrite: Colorimetric, automated hydrazine reduction. EPA/353.1.

Atiyeh, R.M., J. Dominguez, S. Subler, and C.A. Edwards. 2000a. Changes in biochemical properties of cow manure during processing by earthworms (*Eisenia andrei*) and the effects on seedling growth. *Pedobiologia*, 44:709-724.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2000b. Earthworm-processed organic wastes as components of horticultural potting media for growing marigold and vegetable seedlings. *Compost Sci. Util*., 8:215-223.

Atiyeh, R.M., S. Subler, C.A. Edwards, and J.D. Metzger. 1999. Growth of tomato plants in horticultural potting media amended with vermicompost. Pedobiologia 43:724-728.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2001. Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physiochemical properties and plant growth. *Bioresource Technol*., 78:11-20.

Bachman, G.R. and W.E. Davis. 2000. Growth of *Magnolia virginiana* liners in vermicompost-amended media. Proc. SNA Res. Conf., Forty-Fifth Annu. Rpt. p. 65-76.

Browder, J.F., A.X. Niemiera, J.R. Harris, and R.D. Wright. 2005. Growth of container-grown pin oak and Japanese maple as influenced by sulfur and sulfated micronutrients. *HortScience*, 40:1521-1523.

Campbell, C.R. 1992. Determination of total nitrogen in plant tissue by combustion. p. 21-23. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Campbell, C.R. and C.O. Plank 1992. Sample preparation. p. 8-9. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Clark, S. and M. Cavigello. 2005. Suitability of composts as potting media for production of organic vegetable transplants. *Compost Sci. Util*., 13:150-156.

Donohue, S.J. and D.W. Aho. 1992. Determination of P, K, Ca, Mg, Mn, Fe. Al, B, Cu, and Zn in plant tissue by inductively coupled plasma (ICP) emission spectroscopy. p. 37-40.

Eastman, B.R., P.N. Kane, C.A. Edwards. L. Trytek, B. Gunadi, A.L. Sterner, and J.R. Mobley. 2001. The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. Compost Sci. Util. 9:38-49.

Edwards, C.A. June 1995. Historical overview of vermicomposting. *BioCycle*, 36:50-54.

Gale, E.S., D.M. Sullivan, C.G. Cogger, A.I. Bary, D.D. Hemphill, and E.A. Myhre. 2006. Estimating plant-available nitrogen release from manures, composts, and specialty products. *J. Environ. Qual*., 35:2321-2332.

Hadas, A. and R. Portnoy. 1994. Nitrogen and carbon mineralization rates of composted manures incubated in soil. *J. Environ. Qual*., 23:1184-1189.

Handreck, K. 1986 (October). Vermicomposts as components of potting media. *BioCycle*, 27:58-62.

Handreck, K. and N. Black. 2002. Growing media for ornamental plants and turf. 3rd ed. UNSW Press, Sydney.

Hartz, T.K., J.P. Mitchell, and C. Giannini. 2000. Nitrogen and carbon mineralization dynamics of manures and composts. *HortScience*, 35:209-212

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertility: an introduction to nutrient management. 7th ed. Prentice Hall, N.J.

Hidalgo, P.R. and R.L. Harkess. 2002. Earthworm castings as a substrate amendment for chrysanthemum production. *HortScience*, 37:1035-1039.

Hidalgo, P.R., F.B. Matta, and R.L. Harkess. 2006. Physical and chemical properties of substrates containing earthworm castings and effects on marigold growth. *HortScience*, 41:1474-1476.

Kraus, H.T., R.L. Mikkelsen, and S.L. Warren. 2000. Container substrate temperatures affect mineralization of composts. *HortScience*, 35:16-18.

Marschner, H. 1995. Mineral nutrition of higher plants. 2^{nd} ed. Academic Press Limited, San Diego, CA.

McGinnis, M.S. 2007. Sustainable use of vermicomposted hog waste: The use of worm castings as nursery growing substrates amendment to increase water and nutrient efficiency in containerized nursery plant production. North Carolina State Univ., Raleigh, PhD Diss.

Melich et al., 1976

Mokolobate, M.S., and R.J. Haynes. 2002. Comparative liming effect of four organic residues applied to an acidic soil. *Biol. Fert. Soil.*, 35:79-85.

Nair, V.D., D.A. Graetz, and D.O. Dooley. 2003. Phosphorus release characteristics of manure and manure-impacted soils. *Food, Agriculture, & Environment.*, 1:217-223.

Preusch, P.L., P.R. Alder, L.J. Sikora, and T.J. Tworkoski. 2002. Nitrogen and phosphorus availability in composted and uncomposted poultry litter. J. Environ. Qual. 31:2051-2057.

Robinson, J.S. and A.N. Sharpley. 1996. Reaction in soil of phosphorus released from poultry litter. *Soil Sci. Soc. Am. J.*, 60:1583-1588.

Siddique, M.T. and J.S. Robinson. 2003. Phosphorus sorption and availability in soils amended with animal manures and sewage sludge. *J. Enviorn. Qual*., 32:1114-1121.

Stewart, D.P.C., K.C. Cameron, I.S. Cornforth, and B.E. Main. 1998. Release of sulphate, potassium, calcium and magnesium from spent mushroom compost under laboratory conditions. *Biol. Fert. Soil*., 26:146-151.

Tognetti, C., F. Laos, M.J. Mazzarino, and M.T. Hernández. 2005. Composing vs. vermicomposting: a comparison of end product quality. *Compost Sci. Util*., 13:6-13.

Tyler, H.H., S.L. Warren, T.E. Bilderback, and W.C. Fonteno. 1993. Composted turkey litter: I. Effect on chemical and physical properties of a pine bark substrate. *J. Environ. Hort*., 11:131-136.

USDA, 2006. (http://www.ers.usda.gov/Publications/Flo/2006/06Jun/FLO2006.pdf).

Vendrame, W. and K.K. Moore. 2005. Comparison of herbaceous perennial plant growth in seaweed compost and biosolids compost. *Compost Sci. Util*., 13:122-126.

Walker, P., D. Williams, and T.M. Waliczek. 2006. An analysis of the horticultural industry as a potential value-added market for compost. *Compost Sci. Util*., 14:23-31.

Yeager, T.H., C.H. Gilliam, T.E. Bilderback, D.C, Fare, A.X. Niemiera, K.M. Tilt, and S.W. Warren. 2007. Best Management Practices: Guide for Producing Container-Grown Plants. Southern Nursery Association, Marietta, GA.

TABLE 1. Initial properties of substrate components.

Substrate Component	Total N	Organic-N	P	K	Ca	Mg	S	C	C:N
	mg·g^{-1}								
VC[z]	18.0 ± 0.7[y]	12.3 ± 0.4	14.4 ± 1.2	1.4 ± 0.1	73.9 ± 2.0	2.6 ±0.1	2.8 ± 0.2	180 ± 16	10 ± 3
PB[x]	4.4 ± 0.2	3.5 ± 0.2	0.4 ± 0.1	1.4 ± 0.2	5.2 ± 0.1	0.8 ± 0.0	0.4 ± 0.0	505 ± 29	115 ± 12

Substrate Component	Fe	Mn	Zn	Cu	B	Na	CEC	EC	pH
	μg·g^{-1}						meq·100cm^{3}	dS·m^{-1}	
VC	2848 ± 76	554 ± 21	382 ± 25	78.0 ± 3	10.1 ± 0.2	544 ± 20	52.8 ± 0.6	6.9 ± 0.4	5.51 ± 0.06
PB	2201 ± 71	133 ± 6	43 ± 8	11.8 ± 4	2.6 ± 0.1	332 ± 40	---	0.2 ± 0.1	3.87 ± 0.05

[z]VC = Vermicompost

[y]Means and ± 1SE for VC based on eight observations; means and ± 1SE for PB based on three observations; means and ± 1SE for CEC based on two observations

[x]PB = Pine bark

TABLE 2. Initial nutrient content of vermicompost (VC) on a 4-L basis (loading rate).

VC rate	Total N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B
	mg/4L										
10%	2437	1949	186	10033	359	383	387	75	52	11	1.4
20%	4868	3892	372	20041	717	766	773	150	104	21	2.8
30%	7318	5852	560	30130	1078	1152	1161	226	156	32	4.1
40%	9912	7926	758	40810	1460	1560	1573	306	211	43	5.6

TABLE 3. Cumulative nutrients released over time from vermicompost (VC) amended pine bark.

Nut-rient	VC Rate[z] (vol/vol)	Incubation time (wk) 1	2	4	6	8	10	12	14	16
		Content leached (mg/4 L)								
IN-N	0%	0 ± 0[y]	1 ± 0	5 ± 2	7 ± 2	9 ± 2	12 ± 3	13 ± 3	14 ± 3	15 ± 3
	10%	33 ± 5	70 ± 8	93 ± 12	106 ± 13	128 ± 15	157 ± 15	170 ± 15	173 ± 15	174 ± 15
	20%	48 ± 4	108 ± 11	213 ± 18	247 ± 22	278 ± 32	341 ± 33	382 ± 36	406 ± 37	422 ± 36
	30%	65 ± 6	127 ± 15	205 ± 23	239 ± 21	301 ± 20	410 ± 31	475 ± 36	5.24 ± 41	559 ± 43
	40%	132 ± 28	247 ± 39	378 ± 39	426 ± 44	500 ± 44	646 ± 49	734 ± 47	811 ± 52	858 ± 48
	Sig	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)
P	0%	0.9 ± 0.1	1.4 ± 0.1	1.8 ± 0.1	2.1 ± 0.2	2.8 ± 0.3	2.9 ± 0.3	3.8 ± 0.3	4.6 ± 0.4	5.1 ± 0.5
	10%	6.7 ± 0.6	11.6 ± 0.9	22.8 ± 2.0	26.9 ± 2.4	36.8 ± 3.9	42.5 ± 4.5	60.1 ± 5.8	74.5 ± 7.8	86.2 ± 7.9
	20%	4.1 ± 0.6	7.1 ± 0.6	13.7 ± 1.1	16.5 ± 1.8	21.3 ± 2.4	24.2 ± 3.1	31.8 ± 3.5	38.8 ± 4.0	45.1 ± 4.2
	30%	2.3 ± 0.2	3.8 ± 0.2	7.8 ± 0.8	9.3 ± 0.8	12.2 ± 0.8	13.5 ± 0.7	17.1 ± 0.8	20.6 ± 1.1	23.1 ± 1.2
	40%	1.7 ± 0.3	3.5 ± 0.6	7.0 ± 1.1	8.2 ± 1.1	11.3 ± 1.2	12.4 ± 1.3	15.9 ± 1.3	19.3 ± 1.6	21.9 ± 1.5
	Sig*	Q (0.0448)	Q (0.0066)	Q (0.0003)	Q (0.0022)	Q (0.0035)	Q (0.0034)	Q (0.0005)	Q (0.0007)	Q (0.0003)

TABLE 3. (continued)

Nutrient	VC Rate (vol/vol)	Incubation time (wk)								
		1	2	4	6	8	10	12	14	16
		Content leached (mg/4 L for macros)								
Ca	0%	9 ± 2	12 ± 2	17 ± 3	22 ± 4	30 ± 5	32 ± 5	42 ± 6	51 ± 6	58 ± 6
	10%	59 ± 7	95 ± 10	160 ± 14	177 ± 18	209 ± 29	224 ± 29	258 ± 31	282 ± 33	299 ± 33
	20%	120 ± 18	196 ± 22	337 ± 21	382 ± 29	444 ± 34	474 ± 41	536 ± 44	584 ± 46	622 ± 45
	30%	169 ± 20	265 ± 21	480 ± 40	544 ± 43	640 ± 45	663 ± 42	748 ± 41	822 ± 47	873 ± 52
	40%	163 ± 31	317 ± 61	547 ± 73	609 ± 78	756 ± 77	787 ± 77	899 ± 70	997 ± 74	1076 ± 71
	Sig	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)
Mg	0%	2 ± 0	4 ± 0	6 ± 1	8 ± 1	11 ± 1	11 ± 1	16 ± 1	20 ± 1	23 ± 1
	10%	14 ± 2	23 ± 2	37 ± 3	41 ± 4	48 ± 4	52 ± 5	60 ± 5	65 ± 6	68 ± 6
	20%	24 ± 4	40 ± 5	66 ± 4	75 ± 5	86 ± 6	91 ± 7	104 ± 8	113 ± 8	120 ± 8
	30%	31 ± 4	49 ± 4	86 ± 7	97 ± 8	113 ± 8	117 ± 8	133 ± 7	145 ± 9	154 ± 9
	40%	31 ± 6	60 ± 12	100 ± 13	111 ± 14	135 ± 14	141 ± 14	162 ± 13	179 ± 14	193 ± 13
	Sig	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)

TABLE 3. (continued)

Nut-rient	VC Rate (vol/vol)	Incubation time (wk)								
		1	2	4	6	8	10	12	14	16
		Content leached (mg/4 L for macros)								
S	0%	1 ± 0	1 ± 0	1 ± 0	2 ± 0	2 ± 0	2 ± 0	3 ± 0	3 ± 0	3 ± 0
	10%	9 ± 1	13 ± 1	22 ± 2	24 ± 2	29 ± 3	32 ± 2	36 ± 3	47 ± 5	49 ± 5
	20%	14 ± 2	24 ± 3	40 ± 3	46 ± 4	54 ± 5	60 ± 6	70 ± 6	80 ± 7	86 ± 8
	30%	18 ± 2	28 ± 2	51 ± 4	57 ± 4	68 ± 4	71 ± 3	82 ± 3	99 ± 8	106 ± 9
	40%	17 ± 3	32 ± 6	58 ± 7	64 ± 7	79 ± 7	85 ± 7	98 ± 6	114 ± 6	123 ± 6
	Sig	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)	L (<0.0001)

[z] Vol/vol rates equivalent to 17%, 32%, 45%, and 56% w/w dry mass basis.

[y]Means ± 1SE based on four observations.

Sig*0% VC not included in regression analysis

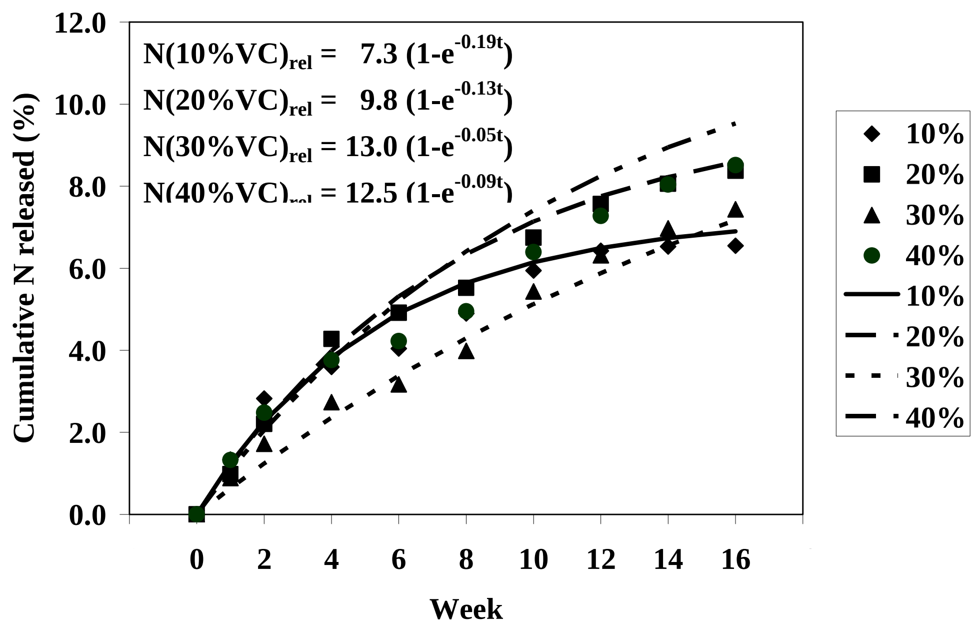
TABLE 4. Substrate solution pH of vermicompost amended pine bark.

Nutrient	VC rate[z] (vol/vol)	Incubation time (wk) 0	1	2	4	6	8	10	12	14	16
		pH									
pH	0%	4.6 ± 0.1[y]	4.6 ± 0.1	4.4 ± 0.1	4.2 ± 0.1	4.3 ± 0.0	4.3 ± 0.0	4.3 ± 0.0	4.2 ± 0.1	4.1 ± 0.0	4.2 ± 0.1
	10%	4.7 ± 0.1	5.1 ± 0.2	5.4 ± 0.3	4.9 ± 0.1	5.0 ± 0.0	5.2 ± 0.1	5.3 ± 0.1	5.2 ± 0.1	5.3 ± 0.1	5.3 ± 0.1
	20%	5.1 ± 0.1	5.2 ± 0.1	5.5 ± 0.1	5.4 ± 0.1	5.5 ± 0.0	5.6 ± 0.1	5.5 ± 0.1	5.6 ± 0.1	5.6 ± 0.1	5.7 ± 0.1
	30%	5.8 ± 0.1	5.9 ± 0.0	6.1 ± 0.1	6.0 ± 0.1	6.1 ± 0.0	6.1 ± 0.0	6.2 ± 0.0	6.2 ± 0.0	6.1 ± 0.0	6.2 ± 0.0
	40%	5.8 ± 0.1	5.9 ± 0.1	6.2 ± 0.1	6.0 ± 0.0	6.0 ± 0.0	6.1 ± 0.0	6.2 ± 0.0	6.1 ± 0.1	6.1 ± 0.0	6.1 ± 0.1
	Sig	L	L	L	LP (29%)	LP (28%)	LP (27%)	Q	LP (26%)	L	LP (25%)

[z]Vol/vol rates equivalent to 17%, 32%, 45%, and 56% w/w dry mass basis.

[y]Means ± SE based on four observations.

[x]NS, nonsignificant, linear (L), or linear-plateau (LP) at 0.05 or *P* value listed. Inflection point for linear-plateau model included in parenthesis.



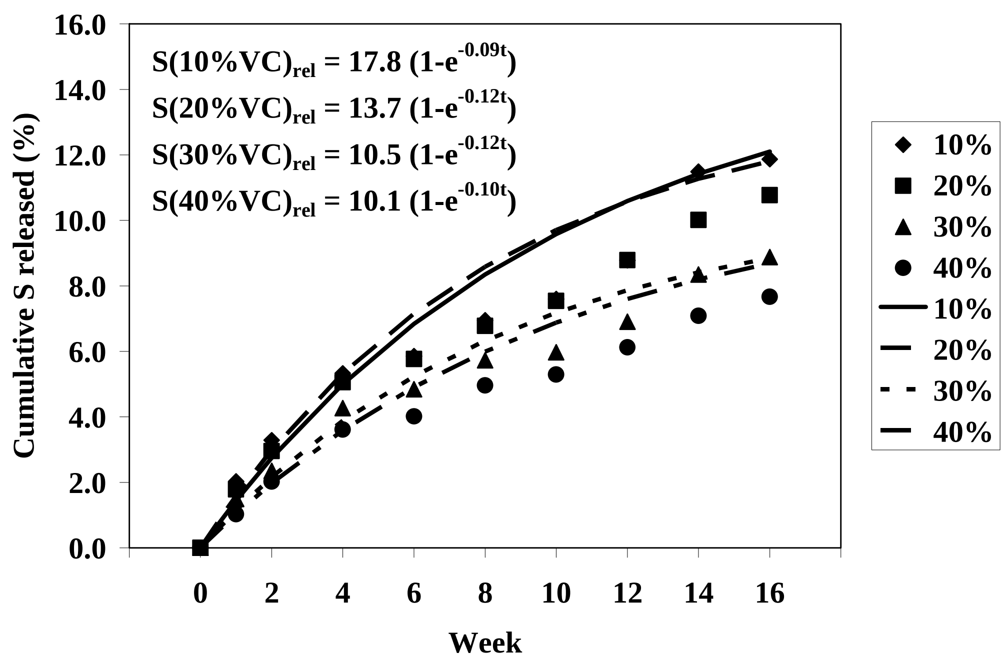


FIGURE 1. First order equations for nitrogen (N) and sulfur (S) expressed as a percentage of initial vermicompost (VC) nutrient inputs. Percent nutrient release (%) = cumulative released into solution (mg) ÷ nutrient loading rate (mg).

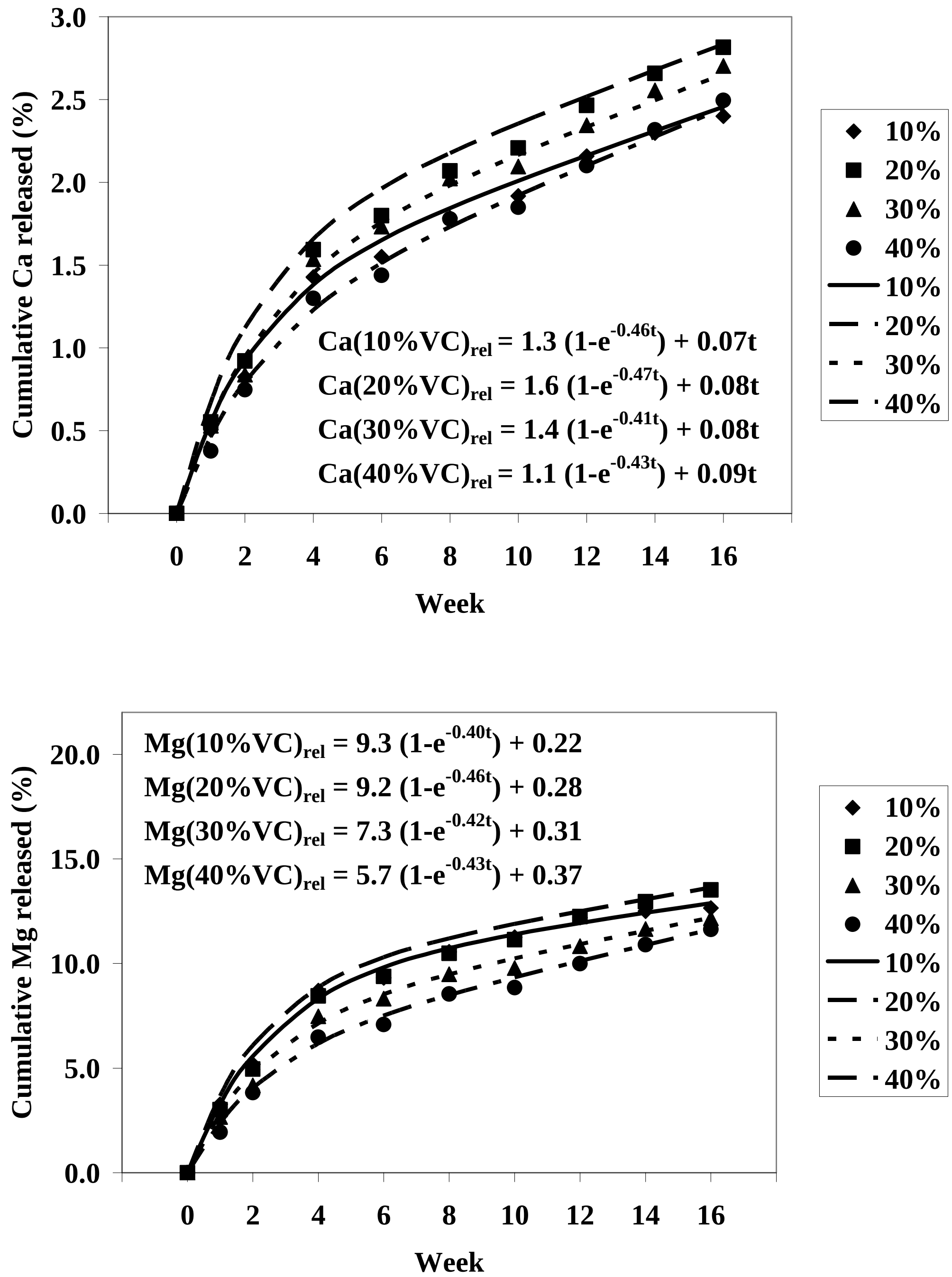


FIGURE 2. Two pool first/zero order models for calcium (Ca) and magnesium (Mg) expressed as a percentage of of initial vermicompost (VC) nutrient inputs. Percent nutrient release (%) = cumulative released into solution (mg) ÷ nutrient loading rate (mg).

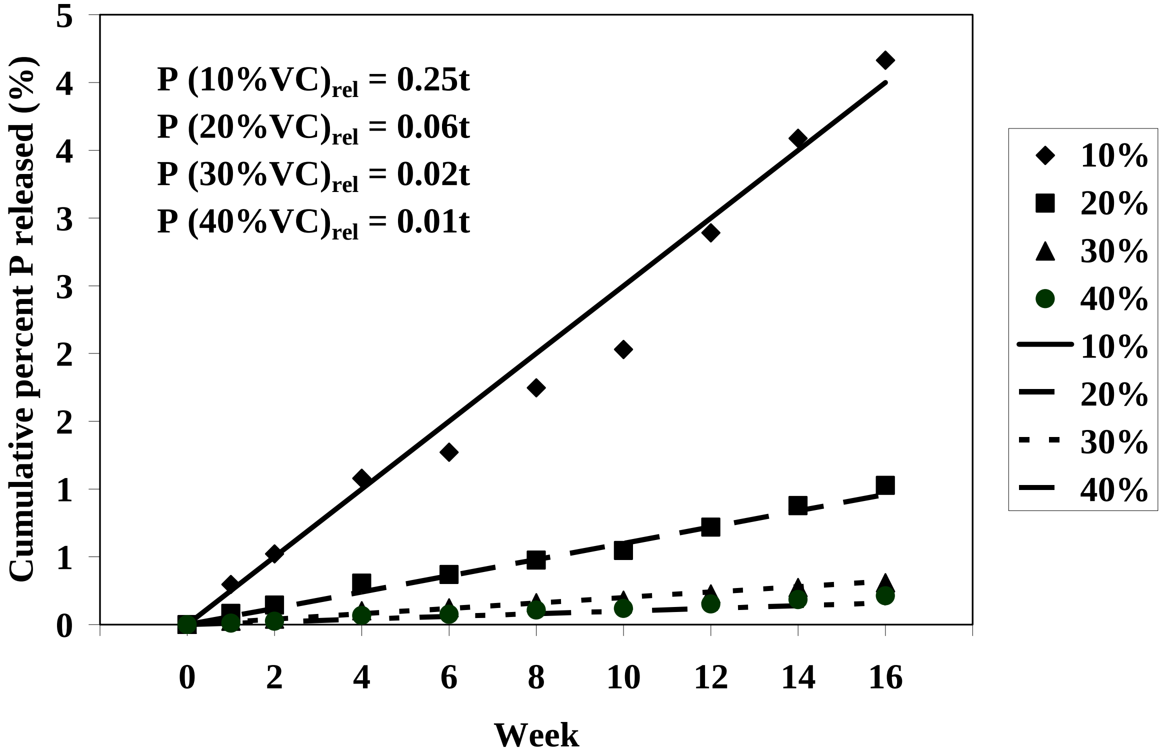


FIGURE 3. Zero order model for phosphorus (P) expressed as a percentage of initial vermicompost (VC) nutrient inputs. Percent nutrient release (%) = cumulative released into solution (mg) ÷ nutrient loading rate (mg).

Chapter 4

Effects of Vermicompost Amended Pine Bark Substrate and Leaching Fraction on Nutrient and Water Use Efficiency, Growth, and Flower Production of *Hibiscus moscheutos* L. 'Luna Blush'

(In the format appropriate for submission to HortScience)

Effects of Vermicompost Amended Pine Bark Substrate and Leaching Fraction on Nutrient and Water Use Efficiency, Growth, and Flower Production of *Hibiscus moscheutos* L. 'Luna Blush'

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Received for publication _____________. This research was funded in part by the North Carolina Agricultural Research Service (NCARS), Raleigh, NC 27695-7643 and the Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Fellowship. Use of trade names in this publication does not imply endorsement by the NCARS or EPA of products named nor criticism of similar ones not mentioned. Appreciation is extended to William M. Reece and Mary Lorscheider for technical assistance and Cavelle Brownie for statistical assistance. From a thesis submitted by M.S.M. in partial fulfillment of the requirements for the PhD degree.

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Subject Category: Soil Management, Fertilization, and Irrigation

Effects of Vermicompost Amended Pine Bark Substrate and Leaching Fraction on Nutrient and Water Use Efficiency, Growth, and Flower Production of *Hibiscus moscheutos* L. 'Luna Blush'

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Additional index words: Container capacity, hog manure, net photosynthesis, worm castings.

Abstract. The objectives of this study were to determine the effects of vermicompost (VC) amended pine bark (PB) and leaching fraction (LF) on water, nitrogen, and phosphorus use efficiency of productivity (WUE_P, NUE_N, and NUE_P), plant growth, and flower production. Hibiscus (*Hibiscus moscheutos* 'Luna Blush' L.) seedlings were grown outdoors on a gravel floor underlain with corrugated plastic for leachate (effluent) collection. Plants were harvested at 47 and 61 days after potting (DAP). The study was a 2 (substrate) x 2 (LF) factorial. The substrate treatments included pine bark amended with 11% sand (by vol.) and 1.8 $kg \cdot m^{-3}$ dolomitic limestone (PBS) and pine bark amended with 20% VC (by vol.) (20VC). The LF treatments were 0.1 and 0.2. Within each substrate (PBS and 20VC), LF 0.1 decreased effluent volume, inorganic nitrogen (IN-N) effluent content, and dissolved reactive

phosphorus (DRP) effluent content by 55%, 64%, and 46%, respectively compared to LF 0.2. Within each LF (0.1 and 0.2), 20VC and PBS had similar effluent volume and IN-N effluent content. At 47 DAP, 20VC and PBS had similar DRP effluent content with 0.1 LF, however 20VC had 32% greater DRP effluent content than PBS with 0.2 LF. At 61 DAP, 20VC had 18% greater DRP effluent content than PBS with 0.1 LF and 72% greater DRP content than PBS with 0.2 LF. At 47 DAP, WUE_P of plants grown in 20VC/0.1 LF was improved compared to plants grown in PBS/0.1 LF and PBS/0.2 LF, however no differences were present at 61 DAP. NUE_N was similar for all four treatments (19%) and NUE_P was greater for the two 20VC treatments (72%) compared to the two PBS treatments (47%). LF did not affect plant growth or flower production for either substrate, however substrate did affect plant growth and flower production. Plants grown in 20VC had greater root, stem, and reproductive tissue dry weight and more flowers than PBS at 47 and 61 DAP. Compared to PBS/0.2LF, a treatment which represents an industry standard, 20VC/0.1LF had greater growth, less IN-N and DRP effluent content, and improved WUE_P at 47 DAP.

A critical component of containerized nursery crop production is water management. Two important aspects of water management are (1) to apply the water to the container efficiently [i.e. maximize interception efficiency (IE) or percentage of water discharged by the irrigation system that reaches the surface of the substrate] and (2) to retain the water in the substrate [i.e. maximize water application efficiency (WAE) or the percentage of water intercepted by the container and remains in the container]. Maximizing IE generally involves infrastructure improvements that include proper design of overhead irrigation systems and/or incorporation of microirrigation systems, while maximizing WAE involves adopting production practices such as cyclic irrigation, irrigation to maintain a minimal leaching fraction (LF = volume leached ÷ volume applied), and/or amending soilless substrates with materials to improve container capacity (CC = water held in a substrate against the force of gravity) (Yeager et. al, 2007). Maximizing WAE is of particular concern as any water leaving the container may contain water soluble plant nutrients. Loading of plant nutrients into watersheds, specifically nitrogen (N) and phosphorus (P), can result in degraded surface water quality (Mallin and Cahoon, 2003). As such, regulatory efforts are underway to reduce nutrient loading from nonpoint sources such as agriculture. While irrigation system improvements may be costly and most applicable to new or expanding nursery operations, implementation of best management practices (BMPs) using existing irrigation systems to improve WAE is feasible for any nursery operation and requires little capital investment.

Several BMPs recommended to improve WAE and reduce nutrient leaching include the use of microirrigation, application of irrigation in a cyclic manner, and minimization of LF (Yeager et. al, 2007). Rathier and Frink (1989) reported microirrigation reduced inorganic N (IN-N) leaching losses up to 50% compared to plants irrigated with overhead irrigation. The use of cyclic irrigation, i.e., the application of total irrigation volume over several time periods during the day, has been reported by several authors to improve WAE and reduce nutrient content in container leachate (Fare et al., 1994; Tyler et al., 1996a). Minimizing LF has also been shown to improve WAE. Several researchers have demonstrated that by reducing influent volumes and LF, the container leachate volumes can be reduced by as much as 68% without affecting plant growth (Fare et al., 1994; Owen, 2006; Tyler et al., 1996b). Tyler et al., (1996b) reported an effluent volume reduction of 63% when LF was reduced from 0.4-0.6 to 0.0-0.2. Similarly, Fare et al. (1994) and Owen (2006) reduced container effluent 54% and 60%, respectively when influent reduction was reduced by 50%. Minimizing LF is also an approach to reduce nutrient container effluent content. Tyler et al., (1996b) reported 66%, 62%, and 57% less NO_3-N, NH_4-N, and dissolved reactive phosphorus (DRP), respectively, in the leachate when LF was reduced from 0.6-0.2 to 0.2-0.0. Fare et al. (1994) reported 53% to 66% less NO_3-N leached when leachate volume was reduced by 50%. Similarly, Owen (2006) reported 60% less DPR lost with container effluent when the LF was reduced by 50%.

Another BMP that can maximize water use efficiency (WUE) and reduce nutrient leaching is the use of a substrate amendment to increase CC (water held in a substrate against the force of gravity) and/or nutrient retention properties (Yeager et al., 2007). Owen (2006) reported a 60% decrease in DRP lost with leachate when pine bark (PB) was amended with an industrial aggregate (clay) compared to PB amended with sand. While composted organic materials can increase CC, some composted materials can increase nutrient leaching losses.

Kuo et. al (1997) reported the 6-week cumulative IN-N leachate content of plants grown in 25% fishwaste compost amended to bark was 245 mg /3-L container greater than the unamended control. However, this material may not have been stabilized based on a reported visual inspection and 83% of the total IN-N leached was lost in the first 4 weeks. A stabilized composted material may serve to increase CC without increasing the nutrient effluent content from containerized crops.

Vermicompost (VC) is a stabilized compost produced by earthworms (i.e. *Eisenia fetida* Savigny, *Lumbricus rubellus* Hoffmeister) under non-thermophilic, aerobic conditions (Edwards, 1995). VC has been shown to improve CC as well as WUE of productivity when amended to pine bark (PB) (McGinnis et al., 2005), however, the nutrient use efficiencies and impact on nutrient effluent content have not been evaluated. Thus, we hypothesized VC amended PB could serve as a BMP by reducing nutrient content leached from the containers while maintaining or improving plant growth. The objectives of this study were to determine the effect of VC amended PB and LF on water, nitrogen, and phosphorus use efficiency of productivity (WUE_P, NUE_N, and NUE_P), plant growth, and flower production of *Hibiscus moscheutos* L.'Luna Blush'.

Materials and Methods

Experimental Design. The study was a 2 (substrates) x 2 (LF) factorial in a randomized complete block design with four blocks and 15 plants per plot (60 plants per block). Substrate treatments included aged (~1 year) PB (<1.25 cm) amended with 20% VC (v/v) (Vermicycle Organics, Wilson, NC) derived from hog manure (20VC), and PB amended with 11% sand (v/v) with dolomitic limestone incorporated at a rate of 1.8 $kg{\cdot}m^{-3}$ (PBS).

Substrates were blended with a 0.76 m^{-3} rotary mixer (Bouldin & Lawson, LLC, McMinnville, Tenn). Irrigation treatments included two influent volumes to yield LFs of 0.1 and 0.2.

Substrate chemical and physical properties. Three samples were collected from VC and PB as well as from each substrate (20VC and PBS). One VC sample was obtained from each of the three 22.7 kg bags prior to blending the VC from all bags, which was then used for the 20VC substrate. Samples were submitted to the N.C. Department of Agriculture and Consumer Services (NCDA&CS), Agronomic Division, Raleigh for mineral nutrient analysis, cation exchange capacity (CEC), EC, and pH (Table 1). Prior to analysis, samples were dried at 65^{o}C and ground with a stainless steel grinder (ED-5 Wiley Mill; Thomas Scientific, Swedesboro, N.J.) to pass ≤ 1 mm screen (Campbell and Plank, 1992). Total carbon (C) and nitrogen (N) concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500; CE Elantech Instruments, Milan, Italy) (Campbell, 1992). Total phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and sodium (Na) concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Wellesley, Mass.), following open-vessel HNO_3 digestion in a microwave digestion system (CEM Corp.; Matthews, NC) (Donohue and Aho, 1992). Electrical conductivity (EC) was determined using a 2 substrate : 1 distilled water extract, and pH was determined using a 1 substrate : 1 distilled water extract. Cation exchange capacity (CEC) was determined by summation of basic cations (excluding Na) and buffer acidity (Mehlich et al., 1976).

Physical property analyses were conducted at the Horticultural Substrates Laboratory, Department of Horticultural Science, N. C. State Univ., Raleigh. On 11 May 2005, four 347.5 cm^3 cylindrical aluminum rings (7.6 cm dia, 7.6 cm ht) and five 101.4 cm^3 cylindrical aluminum rings (7.6 cm dia., 2.2 cm ht) of each substrate were inserted into individual 3.8 L fallow containers and placed on a simulated nursery pad under microirrigation. On 20 July 2004 all cylinders with intact, naturally compacted substrates were extracted. Physical properties [total porosity (TP), air space (AS), CC, available water (AW), unavailable water (UW), and bulk density (D_b)] were measured as described by Tyler et al. (1993).

Plant material, fertilizers, and irrigation. Hibiscus moscheutos L.'Luna Blush' (hibiscus) seeds (Ball Seed Co., Chicago, Ill) were sown in 96-cell flats containing Fafard 4P Mix Professional Formula (Agawam, Mass.) on 28 Mar. 2005. On 11 May 2005, plants were potted into 3.8 L black containers and placed on 16 separate plots at the Horticulture Field Lab at N.C.S.U., Raleigh. Each gravel covered plot (8 x 1 m) was underlain with corrugated plastic at a 2% slope which directed all leachate from each plot to a 19 L collection vessel. Plants were topdressed with controlled release fertilizer (CRF) 19N-2.2P-7.5K (Harrell's, Lakeland, FL, 19-5-9, 3-4 mo., 1.96% ammonical N, 10.04% urea N, and 7% water insoluble N, blended, nutrients had different coatings, P and K had no coating) at a rate of 2.85 g N per 3.8 L (15 g fertilizer per container) on 19 May 2005. For one plant per plot, CRF was divided into two 6 cm x 10 cm bags made from nylon mesh (No-See-Um Mosquito Net; REI, Sumner, Wash.; Catalog Number 601044) and placed on the substrate surface (to simulate top dressing) for quantification of nutrients remaining in the CRF at the study termination. The N and P inputs by the VC to the 20VC substrate treatment were estimated to be 225 mg

N and 8.8 mg P per 3.8 L container as determined by nutrient release equations developed by McGinnis (2007).

Irrigation was applied in a cyclic manner via pressure compensated spray stakes (Acu-Spray Stick; Wade Mfg. Co., Fresno, Calif.; 200 $ml \cdot min^{-1}$) with the daily total volume divided into three applications (1200, 1500, and 1600 HR). Volumes of irrigation water applied (influent) and leached (effluent) for each plot were measured daily, and LF was calculated according to the following equation: LF = volume leached ÷ volume applied. Influent volume per 3.8-L container was measured as the volume collected in a 4 L vessel from one spray stake on each plot, and effluent volume per 3.8-L container was determined by the volume collected in the 19 L leachate vessels at each plot divided by the number of containers on the plot. Influent volumes were adjusted daily to maintain the LF for each plot. Data were compiled to determine cumulative influent volume per container (L) and cumulative effluent volume per container (L). Cumulative volume water retained per container (L) was calculated as the sum of the daily difference between influent and effluent volumes per container. Water use efficiency of productivity (WUE_p) was calculated according to the following equation: WUE_p ($mL \cdot g^{-1}$) = cumulative volume water retained by the substrates at day of harvest ÷ total plant dry mass. Effluent volumes were measured following a rain event with <0.64 cm of rain, however, data collected on these days were not used in the cumulative influent and effluent calculations. A total of 14.5 cm of rain fell on 11 separate days during the study resulting in 9 days of data not included in cumulated totals.

Plant growth and nutrient content. On 27 June 2005 [47 days after potting (DAP)], and 11 July 2005 (61 DAP), two plants 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 constant mass (5 d) prior to obtaining dry weights of all segregated parts. Upon initiation of flowering, the number of open flowers were recorded daily for each plant. At senescence (within 24 hours after opening), flowers were removed, dried, and weighed. From the dry weigh data, the following variables were calculated: reproductive tissue dry weight (RPDW) (g) = flower bud + flower dry weights, total dry weight (g) = root dry weight + stem dry weight + leaf dry weight + flower bud dry weight + flower dry weight, root weight ratio (RWR) ($g \cdot g^{-1}$) = root dry weight ÷ total dry weight, leaf weight ratio (LWR) ($g \cdot g^{-1}$) = leaf dry weight ÷ total dry weight, stem weight ratio (STW) ($g \cdot g^{-1}$) = stem dry weight ÷ total dry weight, and reproductive tissue weight ratio (RPWR) ($g \cdot g^{-1}$) = reproductive tissue dry weight ÷ total dry weight.

All tissues were ground separately via a Foss Tecator Cyclotec™ 1093 sample mill (Cyclotec) (Analytical Instruments, LLC, Golden Valley, Minn.) to pass ≤ 0.5 mm sieve. Stem and roots were ground initially with a Model 4 bench, 1HP Wiley Mill (Thomas Scientific, Swedensboro, N.J.) to pass through a ≤ 6 mm sieve before passing through the Cyclotec. Tissue samples were analyzed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na by the NCDA&CS, Agronomic Division, by methods described previously.

Physiological measures (P_n and g_s). Net CO_2 assimilation (P_n) ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) and stomatal conductance (g_s) ($mol\ H_2O \cdot m^{-2} \cdot s^{-1}$) were measured on individual leaves using a LI-6400 gas analyzer (LI-COR, Lincoln, Neb.) on 1 July 2005 (51 DAP) and 14 July 2005 (64 DAP). Water use efficiency of photosynthesis (WUE_{Pn}) was calculated as: WUE_{Pn} ($mol\ H_2O \cdot \mu mol^{-1}\ CO_2$) = g_s ($mol\ H_2O \cdot m^{-2} \cdot s^{-1}$) ÷ P_n ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$). Measurements were taken on a second most recently matured leaf on a southern exposure on one plant per plot at 1000 and 1700 HR. Both measurements were taken on the same leaf. The 1000 HR measurements were conducted prior to the first irrigation event of the day, and the 1700 HR measurements were conducted between the second and third irrigation cycles. Measured field conditions on 51 DAP at 1000 HR, 51 DAP at 1700 HR, 64 DAP at 1000 HR, and 64 DAP at 1700 HR, respectively, were as follows (n=16): vapor pressure deficit (VPD) = 1.6 ± 0.1, 3.0 ± 0.2, 1.5 ± 0.1, and 1.3 ± 0.1 SE kPa; percent relative humidity (sample chamber) = 70 ± 0.9, 54 ± 2.0, 71 ± 2.1, and 84 ± 1.7 SE; CO_2 (sample chamber) = 378 ± 1.8, 378 ± 1.8, 376 ± 1.6 and 380 ± 1.3 SE $uL \cdot L^{-1}$; and photosynthetically active radiation (PAR) = 1796 ± 9, 1801 ± 22, 1813 ± 19, and 1798 ± 24 SE $umol \cdot m^{-2} \cdot s^{-1}$.

On 15, 16, and 17 July 2005 (65, 66, and 67 DAP), a water stress irrigation regime (aka dry down study) was conducted by withholding irrigation water from one plant per block to determine if the VC and/or LF treatments affected water buffering of the substrate and subsequent plant stress response. Measurements were taken at 1000 and 1500 HR daily until $P_n \leq$ zero at the 1000 HR measurement (which occurred at 67 DAP). Measurements were taken as described above. The measured field conditions for 65 DAP at 1000 HR, 65 DAP at 1500 HR, 66 DAP at 1000 HR, 66 DAP at 1500 HR, and 67 DAP 1000 HR respectively, were as follows (n=16): VPD = 1.5 ± 0.01, 1.7 ± 0.01, 2.1 ± 0.01, 2.7 ± 0.01, and 2.2 ± 0.01 SE kPa; percent relative humidity (sample chamber) = 71 ± 1.7, 80 ± 1.5, 74 ± 1.3, 69 ± 1.1, and 69 ± 1.1 SE; CO_2 (sample chamber) = 378 ± 1.5, 379 ± 1.5, 388 ± 2.5, 406 ± 0.6, and 396 ± 0.5 $uL \cdot L^{-1}$; and PAR = 1801 ± 5, 1793 ± 21, 1806 ± 18, 1800 ± 1, and 1812 ± 17 SE $umol \cdot m^{-2} \cdot s^{-1}$.

Edaphic temperatures. To determine if the VC and/or LF treatments provided temperature buffering to the edaphic environment, calibrated soil temperature probes were place approximately 8 cm below the substrate surface and approximately 2 cm from the north and south walls of one container per plot to measure substrate temperature. Temperatures were measured using a CR23X Micrologger, AM 16/32 multiplexer and Z3537 thermocouple wire (Campbell Sci., Inc. Logan, UT). Temperature was measured at 5 min intervals to calculate and record hourly average, minimum and maximum substrate temperatures. Data from a representative day at representative time points are discussed in the results section.

Nutrient budget, effluent content, and nutrient use efficiency (N and P). A nutrient budget was developed for each treatment to quantify the 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 + nutrient remaining in substrate + nutrient remaining in CRF. The nutrient use efficiency (NUE) for N (NUE_N) and P (NUE_P) were calculated as follows: NUE = {plant adsorbed nutrient ÷ [(added nutrient by CRF and VC) – (nutrient remaining in CRF + nutrient remaining in substrate)]} * 100. Total N and P in plant tissue were determined by NCDA as described previously. Nitrogen in the effluent, substrate, and CRF were quantified as N partitioned as water soluble ammonia (NH_4-N) and nitrate (NO_3-N), and DRP. Inorganic N (IN-N) was calculated as the sum of NH_4-N and NO_3-N.

Effluent samples were analyzed colorimetrically using a UV-visible spectrophotometer (Spectronic 1001, Plus Milton Roy Co., Rochester, NY) for NO_3-N (Calado et al., 1975), NH_4-N (Chaney and Marbach, 1962), and DRP (Murphy and Riley, 1962). Nutrients remaining in the substrate at 61 DAP were extracted using a 1 : 3 extract ratio [30 cc substrate : 90 ml distilled (DI) water], shaken for 1 hour, and filtered through a Whatman #2 filter (Whatman, Inc., Florham Park, N.J.). Nutrients remaining in the CRF were determined by blending CRF prills remaining in the nylon mesh bags at 61 DAP with DI water for 1 min and filtering through Whatman #2 filter. The 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 NH_4-N, NO_3-N, and DRP.

Statistical analysis. All variables were analyzed using Proc ANOVA in SAS version 9.01 (SAS Inst. Inc., Cary, NC) and treatment comparisons were made by Fisher's Protected *LSD*, $P = 0.05$. When the substrate x LF interaction was nonsignificant ($P > 0.05$), data are presented by the main substrate or LF effects. When significant interactions were detected ($P \leq 0.05$), data are presented by substrate x LF simple effects. Additionally, substrate x LF simple effects are presented when no interaction was present but significant differences between both substrate treatments and LF treatments were detected.

Results and Discussion

Substrate physical properties. After 71 DAP, 20VC substrate has greater TP, CC, and AW than PBS, whereas AS and UW was unaffected by substrate treatment (Table 2). Thus, VC at 20% improved CC without reducing AS. The D_b of PBS was greater than 20VC (Table 2). These findings are similar to those reported by McGinnis (2007) where TP, CC, AW, and AS of 53 day *in-situ* compacted substrates were greater for 20% VC amended PB compared to PBS.

Plant growth. Neither LF or substrate x LF interaction affected root, stem, leaf, reproductive tissue dry weights, number of flowers, RWR, LWR, SWR, or RPWR at 47 or 61 DAP, thus results are reported by substrate main effects. Leaf dry weight of hibiscus grown in 20VC was 17% greater than leaf dry weight of hibiscus grown in PBS at 47 DAP, however no difference was detected at 61 DAP (Table 3). At 47 and 61 DAP, hibiscus root dry weight was 114% and 17% greater when grown in 20VC compared to PBS; stem dry weight was 29% and 16% greater when grown in 20VC compared to PBS; and reproductive tissue dry weight was 750% and 217% greater when grown in 20VC compared to plants grown in PBS (Table 3). The total number of flowers produced by 20VC at 61 DAP was 22 times greater than the number of flowers produced by PBS (Table 3), and the average day of first flower for 20VC and PBS were 58 and 61 DAP, respectively (data not presented). At 47 DAP, total dry weight of hibiscus grown in 20VC (40.0 g ± 0.9) was 54% greater than total dry weight of plants grown in PBS (25.9 ± 0.4); and at 61 DAP, total dry weight of hibiscus grown in 20VC (70.6 g ± 2.0) was 27% greater than total dry weight of plants grown in PBS (55.4 ± 1.0). Hidalgo and Harkess (2002) reported similar results with 118% greater top dry weight and 15% more flowers for *Dendranthema* x*grandiflora* (ramat.) Kitam. (chrysanthemum) grown for 10 weeks in a peat moss based substrate amended with 25%VC derived from *Ovine aries* L. (sheep) manure compared to an unamended peat moss control, and six fewer days to first flower of chrysanthemum grown in 25% VC derived from *Bos taurus* L. (cattle) compared to an unamended control. Additionally, Hidalgo et al. (2006) reported 50% greater top dry weight and twice as many flower buds produced by *Tagetes erecta* L. ‘Marvel Orange’ (African marigold) grown for 9 weeks in 25%VC (derived from cattle manure) amended to a pine bark based substrate compared to plants grown in an unamended pine bark based control.

At both 47 and 61 DAP, hibiscus grown in PBS had greater C allocation to leaf tissue compared to hibiscus grown in 20VC, as indicated by LWR (Table 4). At 47 DAP, 20VC allocated relatively more C to roots (indicated by RWR), and at 61 DAP 20VC allocated more C to productive tissue (indicated by RPWR). Allocation of C to root and stem tissue at 47 DAP was greater for 20VC compared to PBS, however by 61 DAP C allocation to root and stem tissue had reversed with greater RWR and SWR for PBS. The reduction of C allocation to root and leaf tissue of hibiscus grown in 20VC at 61 DAP appears to be due to increased flower bud and flower production, as C allocation to reproductive tissue was 23% compare to 9% for PBS, as indicated by RPWR (Table 4).

Irrigation measures. An interaction was not detected for WUE_p, volumes of influent or effluent, or water retained at 47 or 61 DAP, however, results are reported by substrate x LF simple effects to discuss treatment differences. At 47 DAP, plants grown in 20VC/0.1LF had improved WUE_p compared to PBS/0.1LF and PBS/0.2LF, requiring an average 209 ml g^{-1} (or 28%) less water than plants grown in PBS/0.1LF and PBS/0.2LF (Table 5). At 61 DAP, however, WUE_p was unaffected by treatments (Table 5).

As expected influent and effluent volumes within each substrate (PBS and 20VC) were greater for 0.2 LF compared to 0.1 LF at 47 and 61 DAP (Table 5). Averaged over both harvest dates, PBS/0.1LF had 18% less influent volume and 56% less effluent volume than PBS/0.2LF, and 20VC/0.1LF had 25% less influent volume and 51% less effluent volume than 20VC/0.2LF. Others have shown reducing LF by ~50% reduced the effluent volume by

~50% (Fare et al., 1994; Owen, 2006; Tyler et al., 1996b). Within each LF (0.1 and 0.2), 20VC and PBS had similar effluent volumes.

The volume retained by PBS/0.1LF and PBS/0.2LF were similar; however the volume retained by 20VC/0.1LF was less than 20VC/0.2LF (Table 5). This suggests that at a LF of 0.1, the substrate of 20VC was not returned to 100% CC. Even so, the cumulative volume retained by 20VC/0.1 LF was similar to volume retained by the PBS treatments. This significant separation occurred by 10 DAP, with cumulative retained volumes of 20VC/0.2LF (1.65 L ± 0.02) being greater than PBS/0.2LF (1.38 L ± 0.06), PBS/0.1LF (1.26 L ± 0.05) and 20VC/0.1LF (1.41 L ± 0.12) (Figs. 1 and 2.)

Physiological measures (P_n and g_s). P_n and g_s measurements obtained on 51 and 64 DAP were unaffected by interactions and LF, thus only substrate main effects are reported (Table 6). PBS had greater P_n than 20VC at 1000 HR on 51 and 64 DAP and at 1700 HR on DAP 64. In addition, PBS had greater g_s on DAP 51 at 1000 HR and improved WUE_{Pn} on DAP 64 at 1000 HR. Leaf P_n has been reported to decrease due to water stress (Chaves et al., 2002), macronutrient deficiencies, and source/sink imbalances (Paul and Driscoll, 1997; Pieters et al., 2001), however plant growth (dry matter production and yield) is often not correlated with leaf P_n (Elmore, 1980). The greater P_n and g_s observed with plants grown in PBS compared to 20VC is not clear, however, it could be related to stage of development (i.e. 20VC plants are larger) or the fact that nutrient sinks (open flowers) were removed.

No treatments interactions were detected during the dry down study conducted on DAP 65, 66, 67. On 65 DAP, measurements taken at 1000 HR were similar to that reported previously in that treatments differences were observed by substrate treatment, with P_n of

PBS (mean = 17.1 ± 0.8 umol·m^{-2}·s^{-1}) greater than 20VC (mean = 14.7 ± 1.1 umol·m^{-2}·s^{-1}) and WUE_{Pn} of PBS (mean = 0.03 ± 0.001 mmol water · umol CO_2^{-1}) improved compared to 20VC (mean = 0.04 ± 0.002 mmol water · umol CO_2^{-1}) (data not presented). However, on 66 DAP at 1000 HR (the morning following a day of no irrigation), treatments differences were detected by LF, with P_n of plants grown in 0.2 LF (mean = 10.3 ± 1.5 umol·m^{-2}·s^{-1}) greater than plants grown in 0.1 LF treatments (mean = 8.4 ± 0.2 umol·m^{-2}·s^{-1}) (data not presented). Thus, any physiological differences due to substrates observed during regular irrigation of the plants was masked by physiological differences due to LF. It appears that LF 0.2 provided greater water buffering, regardless of substrates, compared to LF 0.1. By 67 DAP, all plants leaves were flaccid and P_n was ≤ 0 (data not presented).

Edaphic temperature. The substrate temperatures at 800, 1100, 1400, and 1700 HR on 17 July 2005 did not differ between treatments on the same aspect of the container. The average temperatures on the north side (n=16) were 27.7 ± 0.2 (0800 HR), 34.4 ± 0.2 (1100 HR), 37.1 ± 0.3 (1400 HR) and 37.3 ± 0.3 (1700 HR) and on the south side (n=16) were 28.2 ± 0.3 (0800 HR), 37.4 ± 0.6 (1100 HR), 39.7 ± 0.4 (1400 HR), and 37.4 ± 0.2 (1700 HR) (data not presented).

Plant tissue nutrient concentration. No interactions were detected for mineral nutrient concentration of any tissue. With the exception of Ca and Mg in reproductive tissues, higher nutrient concentrations were observed with the 0.1 LF treatments, presumably due to greater nutrient availably for plant uptake due to less leaching of nutrients from the container.

In general, tissue nutrient concentrations of hibiscus grown in PBS were equal to or greater than tissue nutrient concentrations of hibiscus grown in 20VC (Tables 7 and 8).

Exceptions to this include concentrations of P in leaf and flower bud tissues; Ca in root, stem, leaf, and flower bud tissues; Cu in stem tissue; and B in root, leaf, and flower bud tissue which were greater in 20VC than PBS. The elevated concentration of these nutrients in plants grown in 20VC compared to PBS are likely due to luxury consumption resulting from greater nutrient availably provided by VC. Although concentrations of most nutrients were less in 20VC than PBS in most tissue, the greater dry mass of plants grown in 20VC resulted in greater total plant content compared to PBS, with the exception of Mn (data not presented).

The differences in nutrient uptake are not believed to be responsible for increased plant growth or flower production. As all treatments were provided with sufficient levels of a complete fertilizer, treatment concentration differences are likely due to luxury consumption of extra nutrients provided by VC and/or dilution effects caused by greater growth of 20VC. For example, although leaf P concentration was greater for 20VC (3.8 $mg \cdot g^{-1}$) compared to PBS (3.2 $mg \cdot g^{-1}$) (Table 7), Walton et al. (2006) reported maximum top growth and flower production of hibiscus at daily P rates of 3.1 $mg \cdot L^{-1}$ which resulted in a P foliar concentration of 1.6 $mg \cdot g^{-1}$, representing half the foliar P concentration observed herein. Others have concluded increased plant growth in VC amended substrates compared to non-amended substrates was not due to nutrients associated with VC, but perhaps due to synergistic effects of a variety of factors, including improved physical properties, influence of hormone-like substances and humic substances and/or the presence of beneficial microorganisms (Arancon et al., 2004; Tomati and Galli, 1995).

Nutrient budget, effluent nutrient content, and nutrient use efficiency (N and P). Interactions were detected for both NH_4 and P effluent content at 47 and 61 DAP, thus substrate x LF simple effects are presented (Table 9). Effluent content of IN-N was reduced by 65% for PBS and 48% for 20VC when irrigated with 0.1 LF compared to 0.2 LF at both 47 and 61 DAP. These results are similar to ~64% IN-N effluent content reduction reported by Tyler et al. (1996b) and ~60% NO_3-N effluent content reduction reported by Fare at al. (1994) when effluent volumes were reduced by more than 50%. Effluent content of IN-N was similar for both PBS and 20VC irrigation with similar LF (0.1 and 0.2), however the N species differed. Greater NO_3-N effluent content was detected in 20VC treatments compared to PBS treatments, whereas greater NH_4-N effluent content was detected in the PBS treatments compared to the 20VC treatments (Table 9). A large percentage of IN-N as NH_4-N in PBS effluent would be expected due to CRF formulation which contained 63% of IN-N as ammonical and urea N, and a large percentage of IN-N as NO_3-N in of 20VC effluent would be expected as NO_3-N has been shown to comprise >99% of IN-N mineralized by VC (McGinnis, 2007). Additionally, the lower NH_4-N effluent content of 20VC compared to PBS for each LF may be due to retention of NH_4-N originated from CRF by the CEC associated with the VC and/or nitrification to NO_3-N by microorganisms associated with the VC. The percent applied N that was recovered in effluent was 0.7%, 2.1% 1.3%, and 2.4% for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF, respectively.

Of total N inputs with CRF and VC, RN_N was 20%, 19%, 22% and 22% for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF, respectively (Table 10). Of the RN_N content, 95%, 88%, 93%, and 88% was in plant tissue and 4%, 11%, 6%, and 11% was in the effluent for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF, respectively. Recovered nutrient as water extractable N in the substrate was ≤ 1%, whereas 0.1% N was left in the CRF. NUE_N for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF was 19%, 17%, 20%, and 19%, respectively. Others have reported similar NUE_N as outlined by Lea-Cox and Ristvey (2003).

Effluent content of DRP was reduced by 45% for both PBS and 20VC when irrigated with 0.1 LF compared to 0.2 LF at both DAP 47 and 61. These results have similar trends to that reported by Tyler et al. (1996b) and Owen (2006) where DRP was reduced by ~57% and 60%, respectively, when effluent volume was reduced by ~50%. At 61 DAP, DRP effluent content of 20VC was ~71% greater than PBS at each 0.1 and 0.2 LF (Table 9). The percent applied P that was recovered in effluent was 5%, 9%, 8%, and 15% for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF, respectively. Thus, while reducing LF reduced DPR effluent contents, 20VC increased DRP effluent content.

Of total P inputs from CRF and VC, RN_P was 54%, 56%, 82%, and 90% for PBS-0.1LF, PBS-0.2LF, 20VC-0.1LF, and 20VC-0.2LF, respectively (Table 11). Of the RN_P content, 87%, 78%, 84%, and 77% was in plant tissue, 10%, 17%, 10%, and 17% was in effluent, and 3%, 5%, 6%, and 6% in the substrate for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF, respectively. Recovered nutrient as water extractable DRP left in the CRF was 0.5%. NUE_P for PBS/0.1LF, PBS/0.2LF, 20VC/0.1LF, and 20VC/0.2LF was 48%, 45%, 72%, and 73%, respectively. Owen (2006) and Lea-Cox and Ristvey (2003) reported similar NUE_P for PBS. Relatively high NUE_P for 20VC reported herein may be due to the ability of VC to retain P.

In summary, hibiscus grown in 20VC were larger and produced more reproductive tissue compared to hibiscus grown in PBS, regardless of the LF, thus essentially shortening production time of the crop. The WUE_P was improved for 20VC/0.1 LF compared to all other treatments at 47 DAP, however no differences were detected at 61 DAP. Although 20VC did not result in greater effluent volume or greater IN-N effluent content compared to PBS, 20VC did result in greater DRP effluent content compared to PBS. The reduction and/or elimination of P as a fertilizer input when using VC may provide sufficient P for plant growth and reduce DRP effluent content, thus maximinize crop growth while minimizing environmental impact.

Literature Cited

Arancon, N.Q., C.A. Edwards, A. Atiyeh, and J.D. Metzer. 2004. Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. Bioresource Technol. 93:139-144.

Calado, D.A., M. Haroon, L.E. Schrader, and V.L. Youngs. 1975. Rapid colorimetric determination of nitrate in plant tissue. Commun. Soil Sci. Plant Anal. 6:71-80.

Campbell, C.R. 1992. Determination of total nitrogen in plant tissue by combustion. p. 21-23. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Campbell, C.R. and C.O. Plank 1992. Sample preparation. p. 8-9. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Chaney, D.A. and E.P. Marbach. 1962. Modified reagents for determination of urea and ammonia. Clin. Chem. 8:130-132.

Chaves, M.M., J.S. Pereira, J. Maroco, M.L. Rodrigues, C.P.P Ricardo, M.L. Osorio, I. Carvalho, T. Faria, and C. Pinheiro. 2002. How plants cope with water stress in the field. Photosynthesis and growth. Ann. Bot. 89:907-916.

Donohue, S.J. and D.W. Aho. 1992. Determination of P, K, Ca, Mg, Mn, Fe. Al, B, Cu, and Zn in plant tissue by inductively coupled plasma (ICP) emission spectroscopy. p. 37-40. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Edwards, C.A. June 1995. Historical overview of vermicomposting. BioCycle 36:50-54.

Elmore, C.D. 1980. The paradox of no correlation between leaf photosynthetic rates and crop yields. P. 155-167. In J.D. Hesketh and J.W. Jones (ed). Predicting photosynthesis for ecosystem models. Vol 2. CRC Press, Boca Raton, Fla.

Fare, D.C., C.H. Gilliam, and G.J. Keever. 1994. Cyclic irrigation reduces container leachate nitrate-nitrogen concentration. HortScience 29:1514-1517.

Hidalgo, P.R. and R.L. Harkess. 2002. Earthworm castings as a substrate for amendment for chrysanthemum production. HortScience 37:1035-1039.

Hidalgo, P.R., F.B. Matta, and R.L. Harkess. 2006. Physical and chemical properties of substrates containing earthworm castings and effects on marigold growth. HortScience 41:1474-1476.

Kuo, S., R.L. Hummel,. E.J. Jellum, and D. Privett. 1997. Fishwatste compost effects on Rhododendron growth and nitrogen leaching and transformation. J. Environ. Qual. 1997:733-739.

Lea-Cox, J.D. and A.G. Ristvey. 2003. Why are nutrient uptake efficiencies so low in ornamental plant production? Proc. SNA Res. Conf., Forth-eighth Annu. Rtp. p. 107-111.

Mallin, M.A., and L.B. Cahoon. 2003. Industrialized animal production – a major source of nutrient and microbial pollution to aquatic ecosystems. Population and Envr. 5:369-385.

McGinnis, M.S. 2007. Sustainable use of vermicomposted hog waste: The use of worm castings as nursery growing substrates amendment to increase water and nutrient efficiency in containerized nursery plant production. North Carolina State Univ., Raleigh, PhD Diss.

McGinnis, M., T. Bilderback, and S. Warren. 2005. Vermicompost: Improving water use efficiency in nursery crop production. Proc. SNA. Res. Conf., Fifthith Annu. Rpt. p. 50:73-77.

Mehlich, A., S.S. Bowling, and A.L. Hatfield. 1976. Buffer pH acidity in relation to nature of soil acidity and expression of lime requirement. Commun. Soil Sci. Plant Anal. 7(3)25363.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36.

Owen, Jr., J.S. 2006. Clay amended soilless substrates: Increase water and nutrient efficiency in containerized crop production. North Carolina State Univ., Raleigh, PhD Diss.

Paul, M.J. and S.P. Driscoll. 1997. Sugar repression of photosynthesis: the role of carbohydrates in signaling nitrogen deficiency through source:sink imbalance. Plant, Cell, and Environ. 20:110-116.

Pieters, A.J, M.J. Paul, and D.W. Lawlor. 2001. Low sink demand limits photosynthesis under Pi deficiency. J. Exp. Bot. 52:1083-1091.

Rathier, T.M. and C.R. Frink. 1989. Nitrate in runoff water from container grown juniper and Alberta spruce under different irrigation and N fertilization regimes. J. Environ. Hort.:32-35.

Tomati, U. and E. Galli. 1995. Earthworms, soil fertility, and plant productivity. Acta Zoo. Fennica. 196:11-14.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. J. Environ. Hort. 14:194-198.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996b. Reduced leaching fractions improve irrigation use efficiency and nutrient efficacy. J. Environ. Hort. 14:199-204.

Tyler, H.H., S.L. Warren, T.E. Bilderback, and W.C. Fonteno. 1993. Composted turkey litter: I. Effect on chemical and physical properties of a pine bark substrate. J. Environ. Hort. 11:131-136.

Walton, K.N., H.T. Kraus, and S.L. Warren. 2006. Finding the P rate and N:P ratio for maximum growth of container-grown herbaceous perennials. Proc. SNA. Res. Conf., Fifty-first Annu. Rpt. p. 51:49-51.

Yeager, T.H., C.H. Gilliam, T.E. Bilderback, D.C, Fare, A.X. Niemiera, K.M. Tilt, and S.W. Warren. 2007. Best Management Practices: Guide for Producing Container-Grown Plants. Southern Nursery Association, Marietta, GA.

Table 1. Initial nutrient concentrations of pine bark (PB) and vermicompost (VC) substrates and substrate components.

Substrate[z]	N	P	K	Ca	Mg	S	C	CEC
	mg·g^{-1}							cmol
PBS	1.9 ± 0.2[y]	0.3 ± 0.0	0.66 ± 0.0	4.3 ± 0.2	1.2 ± 0.0	0.1 ± 0.0	264 ± 30	--
20VC	6.3 ± 0.2	3.9 ± 0.2	1.05 ± 0.0	26.2 ± 1.8	1.3 ± 0.1	0.2 ± 0.0	359 ± 21	--
100PB	3.1 ± 0.2	0.3 ± 0.0	1.08 ± 0.1	3.4 ± 0.1	0.8 ± 0.1	0.3 ± 0.0	440 ± 23	--
100VC	13.9 ± 1.6	10.8 ± 0.5	1.08 ± 0.0	87.8 ± 1.3	2.4 ± 0.0	1.8 ± 0.0	173 ± 18	85 ± 10

Substrate	Fe	Mn	Zn	Cu	B	Na	EC	pH
	µg·g^{-1}						dS·m^{-1}	
PBS	2012 ± 49	75 ± 1	18 ± 0.5	5 ± 0.1	0.0 ± 0.0	227 ± 16	0.18 ± 0.01	4.63 ± 0.1
20VC	2952 ± 97	266 ± 26	110 ± 9.9	34 ± 2.0	1.5 ± 0.1	346 ± 40	1.64 ± 0.09	5.31 ± 0.1
100PB	3193 ± 106	98 ± 1	26 ± 0.7	7 ± 0.2	0.0 ± 0.0	213 ± 25	0.18 ± 0.00	3.91 ± 0.0
100VC	3052 ± 129	741 ± 10	322 ± 4.8	104 ± 11.7	8.7 ± 0.5	526 ± 24	3.05 ± 0.23	6.11 ± 0.1

[z]PBS = 8 pine bark : 1 sand with 1.8 kg·m^{-3} dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.); 100PB = 100% pine bark; and 100VC = 100% vermicompost.

[y]Means ± 1 SE based on 3 observations.

Table 2. Physical properties of pine bark amended substrates 71 days after potting.

Substrate[z]	Total porosity[y]	Air space[x]	Container capacity[w]	Available water[v]	Unavailable water[u]	Bulk density
	Percent volume					$g \cdot cm^{-3}$
PBS	76 b ± 2[ts]	23 a ± 2	53 b ± 1	24 b ± 1	30 a ± 1	0.41 a ± 0.01
20VC	85 a ± 0	22 a ± 1	62 a ± 2	31 a ± 2	31 a ± 1	0.27 b ± 0.00

[z]PBS = 8 pine bark : 1 sand with 1.8 $kg \cdot m^{-3}$ dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.)

[y]Based upon percent volume air and water of a 7.6 x 7.6 cm core at 0 kPa.

[x]Measured as percent volume air of a 7.6 x 7.6 cm core at 0 kPa.

[w]Measured as percent volume water of a 7.6 x 7.6 cm core after drainage at 0 kPa.

[v]Available water = container capacity - unavailable water.

[u]Based upon percent volume water retained of a 7.6 x 7.6 cm core at 1500 kPa.

[t]Each mean ± 1 SE based on four observations.

[s]Means within each variable followed by the same letter are not significantly different as determined by F test at $P \leq 0.05$.

Table 3. Effect of substrate on dry tissue weights and flower number of *Hibiscus moscheutos* 'Luna Blush' at 47 and 61 days after potting (DAP).

DAP	Substrate[z]	Root dry weight	Stem dry weight	Leaf dry weight	Reproductive tissue dry weight[y]	Flower number[x]
		g				
47	PBS	5.7 b ± 0.2[wv]	5.6 b ± 0.1	14.4 b ± 0.2	0.2 b ± 0.0	0.0 a ± 0.0
	20VC	12.2 a ± 0.4	9.2 a ± 0.2	16.9 a ± 0.5	1.7 a ± 0.2	0.0 a ± 0.0
61	PBS	19.2 b ± 0.6	12.9 b ± 0.3	18.1 a ± 0.4	5.2 b ± 0.3	0.4 b ± 0.1
	20VC	22.5 a ± 0.8	15.0 a ± 0.6	16.7 a ± 0.6	16.4 a ± 0.5	8.8 a ± 0.8

[z]PBS = 8 pine bark : 1 sand with 1.8 kg·m^{-3} dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.).

[y]Reproductive tissue dry weight = flower bud + flower dry weights.

[x]Flower number = number of senesced flowers removed prior to harvest.

[w]Each mean ± standard error is based on eight observations; substrate treatments averaged over leaching fraction.

[v] Means within each variable within each DAP followed by the same letter are not significantly different as determined by F test at $P \leq 0.05$.

Table 4. Effect of substrate on carbon allocation measures of *Hibiscus moscheutos* ‘Luna Blush’ at 47 and 61 days after potting (DAP).

DAP	Substrate[z]	RWR[y]	SWR[x]	LWR[w]	RPDWR[v]
47	PBS	0.22 b ± 0.01[ut]	0.22 b ± 0.00a	0.56 a ± 0.00	0.01 b ± 0.00
	20VC	0.30 a ± 0.01	0.23 a ± 0.00a	0.42 b ± 0.01	0.04 a ± 0.01
61	PBS	0.35 a ± 0.01	0.23 a ± 0.00a	0.33 a ± 0.01	0.09 b ± 0.01
	20VC	0.32 b ± 0.01	0.21 b ± 0.00b	0.24 b ± 0.01	0.23 a ± 0.01

[z] PBS = 8 pine bark : 1 sand with 1.8 $kg \cdot m^{-3}$ dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.)

[y]RWR (root weight ratio) = root weight (g) ÷ total dry weight.

[x]SWR (stem weight ratio) = stem dry weight (g) ÷ total dry weight (g).

[w]LWR (leaf weight ratio) = leaf dry weight (g) ÷ total dry weight (g).

[v]RPDWR (reproductive tissue weight ratio) = flower bud dry weight (g) + flower dry weight (g) ÷ total dry weight (g)

[u]Each mean ± standard error is based on eight observations; substrate treatments averaged over leaching fraction.

[t]Means within each variable within each DAP followed by the same letter are not significantly different as determined by F test at $P \leq 0.05$.

Table 5. Effect of substrate and leaching fraction (LF) on water use efficiency and cumulative irrigation water management measures of *Hibiscus moscheutos* 'Luna Blush' at 47 and 61 days after potting (DAP).

DAP	Substrate[z]	LF[y]	WUE_p[x]	Influent	Effluent	Water retained
			mL g^{-1}	L per 3.8 L container		
47	PBS	0.1	728 a ± 23[wv]	21.7 c ± 0.3	2.9 b ± 0.2	18.7 b ± 0.2
		0.2	764 a ± 70	26.2 b ± 1.9	6.6 a ± 0.5	19.6 b ± 1.8
	20VC	0.1	537 b ± 12	24.9 bc ± 0.5	3.4 b ± 0.8	21.5 b ± 0.4
		0.2	675 ab ± 27	33.8 a ± 1.9	6.9 a ± 0.5	26.9 a ± 1.5
61	PBS	0.1	550 a ± 18	35.4 c ± 0.4	5.0 b ± 0.3	30.4 b ± 0.5
		0.2	599 a ± 46	43.8 b ± 2.6	11.1 a ± 0.5	32.7 b ± 2.5
	20VC	0.1	496 a ± 30	39.8 bc ± 0.9	5.6 b ± 0.1	34.2 b ± 0.8
		0.2	583 a ± 31	52.8 a ± 2.3	11.6 a ± 0.3	41.2 a ± 2.0

[z] PBS = 8 pine bark : 1 sand with 1.8 kg·m^{-3} dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.).

[y]LF = volume leached ÷ volume applied.

[x]WUE_p (water use efficiency of productivity) = volume of water retained by substrate (mL) ÷ total plant dry weight (g).

[w]Each mean ± standard error is based on four observations.

[v]Means within each variable within each DAP followed by the same letter are not significantly different as determined by Fisher's Protected LDS at $P \leq 0.05$.

Table 6. Effect of substrate on net photosynthesis (P_n), stomatal conductance (g_s), and water use efficiency of photosynthesis (WUE_{Pn}) of *Hibiscus moscheutos* 'Luna Blush'. at 51 and 64 days after potting (DAP).

DAP	Time	Substrate[z]	P_n ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	g_s ($mmol \cdot m^{-2} \cdot s^{-1}$)	WUE_{Pn}[y] (mmol water · umol CO_2^{-1})
51	1000 HR	PBS	18.2 a ± 0.9[xw]	0.74 a ± 0.05	0.040 a ± 0.002
		20VC	14.9 b ± 1.0	0.58 b ± 0.06	0.039 a ± 0.003
	1700 HR	PBS	17.2 a ± 0.8	0.31 a ± 0.05	0.017 a ± 0.002
		20VC	14.8 a ± 1.0	0.27 a ± 0.04	0.018 a ± 0.002
64	1000 HR	PBS	18.2 a ± 0.9	0.55 a ± 0.04	0.030 b ± 0.001
		20VC	15.8 b ± 1.0	0.55 a ± 0.05	0.035 a ± 0.001
	1700 HR	PBS	17.8 a ± 0.9	0.59 a ± 0.04	0.033 a ± 0.002
		20VC	14.8 b ± 0.6	0.55 a ± 0.05	0.037 a ± 0.003

[z]PBS = 8 pine bark : 1 sand with 1.8 $kg \cdot m^{-3}$ dolomitic lime (v/v); 20VC = 20% vermicompost amended pine bark (by vol.)

[y]$WUE_{Pn} = g_s \div P_n$

[x]Each mean ± standard error is based on eight observations.

[w]Means within each variable within each DAP and time followed by the same letter are not significantly different as determined by F test at $P \leq 0.05$.

Table 7. Effect of substrate on macronutrient concentration of *Hibiscus moscheutos* 'Luna Blush' tissues at 61 days after potting.

Tissue	Substrate[z]	N	P	K	Ca	Mg	S
		$mg \cdot g^{-1}$					
Root	PBS	6.5 a ± 0.2[yx]	2.4 a ± 0.1	14.1 a ± 0.4	4.0 b ± 0.1	4.8 a ± 0.1	1.7 a ± 0.1
	20VC	4.1 b ± 0.2	3.3 b ± 0.1	12.4 b ± 0.5	6.2 a ± 0.2	4.7 a ± 0.1	1.5 a ± 0.0
Stem	PBS	3.7 a ± 0.2	1.9 a ± 0.1	15.1 a ± 0.3	5.9 b ± 0.1	3.3 a ± 0.1	0.8 a ± 0.0
	20VC	2.4 b ± 0.1	2.0 a ± 0.1	11.4 b ± 0.3	11.3 a ± 0.4	2.1 b ± 0.1	0.8 a ± 0.0
Leaf	PBS	12.3 a ± 1.4	3.2 b ± 0.1	15.2 a ± 0.5	16.8 b ± 0.6	9.4 a ± 0.3	1.8 a ± 0.1
	20VC	10.1 a ± 0.4	3.8 a ± 0.2	14.5 a ± 0.4	28.2 a ± 0.9	6.2 b ± 0.2	1.7 a ± 0.1
Reproductive	PBS	22.4 a ± 0.9	4.3 b ± 0.0	23.6 a ± 0.2	11.6 b ± 0.3	8.3 a ± 0.1	1.9 a ± 0.0
	20VC	19.2 b ± 0.4	4.5 a ± 0.1	24.1 a ± 0.2	14.7 a ± 0.4	5.5 b ± 0.1	1.8 b ± 0.1

[z] PBS = 8 pine bark : 1 sand with 1.8 $kg \cdot m^{-3}$ dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by volume)

[y]Each mean ± standard error is based on eight observations.

[x]Means within each variable within each tissue followed by the same letter are not significantly different as determined by F test at $P \leq 0.05$.

Table 8. Effect of substrate on micronutrient content of *Hibiscus moscheutos* 'Luna Blush' tissues at 61 days after potting.

Tissue	Substrate[z]	Fe	Mn	Zn	Cu	B	Na
		$ug{\cdot}g^{-1}$					
Root	PBS	285 a ± 39	86 a ± 2	57 a ± 3	21 a ± 1.3	12 b ± 0.2	3317 a ± 131
	20VC	271 a ± 74	28 b ± 3	56 a ± 5	21 a ±1.5	13 a ± 0.3	2889 a ± 103
Stem	PBS	79 a ± 21	110 a ± 2	37 a ± 2	4 b ± 0.2	17 a ± 0.3	1455 a ± 39
	20VC	40 a ± 2	23 b ± 2	29 b ± 1	6 a ± 0.3	17 a ± 0.5	1227 b ± 62
Leaf	PBS	654 a ± 93	611 a ± 24	84 a ± 5	5 a ± 0.3	30 b ± 0.6	721 a ± 27
	20VC	365 a ± 108	141 b ± 19	67 a ± 8	6 a ± 0.6	40 a ± 1.2	637 a ± 39
Reproductive	PBS	117 a ± 8	332 a ± 13	70 a ± 2	12 a ± 0.5	27 b ± 0.2	377 a ± 11
	20VC	125 a ± 51	67 b ± 5	55 b ± 3	13 a ± 1.1	30 a ± 0.3	392 a ± 17

[z] PBS = 8 pine bark : 1 sand with 1.8 $kg{\cdot}m^{-3}$ dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by volume)

[y]Each mean ± standard error is based on eight observations.

[x]Means within each variable within each tissue followed by the same letter are not significantly different as determined by F test at s$P \leq 0.05$.

Table 9. Cumulative nutrient content leached at 61 days after potting by *Hibiscus moscheutos* 'Luna Blush' grown in two substrates with two leaching fraction (LF) irrigation regimes.

DAP[z]	Substrate[y]	LF[x]	NO_3-N[w]	NH_4-N[w]	IN-N[w]	DRP[w]
			mg per 3.8 L container			
47	PBS	0.1	5.4 c ± 0.8[uw]	14.4 b ± 0.9	19.8 b ± 1.6	14.6 c ± 1.4
		0.2	20.6 bc ± 6.4	35.8 a ± 2.1	56.4 a ± 7.3	28.3 b ± 2.1
	20VC	0.1	31.0 b ± 2.8	5.6 c ± 0.7	36.6 b ± 2.1	20.1 c ± 2.2
		0.2	55.1 a ± 6.5	15.6 b ± 2.2	70.7 a ± 8.0	37.4 a ± 3.5
61	PBS	0.1	5.7 c ± 0.8	15.2 b ± 1.0	20.9 b ± 1.7	17.1 c ± 1.9
		0.2	22.4 bc ± 7.7	37.0 a ± 2.2	59.3 a ± 8.5	30.9 b ± 2.4
	20VC	0.1	32.4 b ± 2.7	6.0 c ± 0.6	38.4 b ± 2.1	29.0 b ± 2.3
		0.2	55.5 a ± 6.5	16.9 b ± 2.2	72.3 a ± 8.1	53.2 a ± 2.1

[z]Days after potting.

[y]PBS = 8 pine bark : 1 sand with 1.8 kg·m^{-3} dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.).

[x] LF = volume leached ÷ volume applied.

[w]NO_3-N = nitrate nitrogen; NH_4-N = ammonium nitrogen, IN-N = inorganic nitrogen, and DRP = dissolved reactive phosphorus

[v]Each mean ± standard error is based on four observations.

[u]Means within each variable within each DAP followed by the same letter or letters are not significantly different as determined by Fisher's Protected LSD at P=0.05.

Table 10. Nitrogen partition of *Hibiscus moscheutos* 'Luna Blush' grown in two substrates and two leaching fractions (LF) at 61 days after potting.

Nitrogen partition	PBS[z]		20VC[z]	
	0.1	0.2	0.1	0.2
Inputs				
Fertilizer (mg)	2850	2850	2850	2850
Vermicompost (mg)	0	0	225	225
Outputs				
Effluent NO_3-N (mg)	5.7	22.4	32.4	55.5
Effluent NH_4-N (mg)	15.2	37.0	6.0	16.9
Hibiscus				
Root (mg)	130	119	100	87
Stem (mg)	53	42	41	31
Leaf (mg)	252	188	175	161
Bud/Flower (mg)	108	122	310	311
Remaining in system				
Substrate NO_3-N (mg)	2.3	4.1	3.8	4.0
Substrate NH_4-N (mg)	4.2	4.1	6.1	6.5
Fertilizer NO_3-N (mg)	0.08	0.10	0.02	0.07
Fertilizer NH_4-N (mg)	0.45	0.59	0.49	0.49
RN_N[y] (mg)	569	536	672	669
RN_N[x] (%)	20	19	22	22
NUE_N[x] (%)	19	17	20	19

[z]PBS = 8 pine bark : 1 sand with 1.8 kg·m^{-3} dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.)

[y]RN_N (mg) = N in plant + effluent + substrate + fertilizer prills.

[x]RN_N (%) = (N in plant + effluent + substrate + fertilizer prills) ÷ nitrogen inputs

[w]NUE = {plant adsorbed nutrient (mg) ÷ [applied nutrient (mg) – nutrient remaining in CRF prill – nutrient remaining in substrate]} * 100

Table 11. Phosphorus partition of *Hibiscus moscheutos* 'Luna Blush' grown in two substrates and two leaching fractions (LF) at 61 days after potting.

Phosphorus partition	PBS[z]		20VC[z]	
	0.1	0.2	0.1	0.2
Inputs				
Fertilizer (mg)	330	330	330	330
Vermicompost (mg)	0	0	18.77	18.77
Outputs				
Effluent (mg)	17.1	30.9	29.1	53.2
Hibiscus				
Root (mg)	46	44	75	71
Stem (mg)	27	23	32	29
Leaf (mg)	60	55	62	65
Bud/Flower (mg)	22	22	71	76
Remaining in system				
Substrate (mg)	9.5	13.4	25.8	28.0
Fertilizer prills (mg)	0.6	0.7	0.5	0.4
RN_P[y] (mg)	179	184	286	313
RN_P[x] (%)	54	56	82	90
NUE_P[w] (%)	48	45	72	73

[z] PBS = 8 pine bark : 1 sand with 1.8 $kg \cdot m^{-3}$ dolomitic limestone (v/v); 20VC = 20% vermicompost amended pine bark (by vol.)

[y] RN_P (mg) = N in plant + effluent + substrate + fertilizer prills.

[x] RN_P (%) = (N in plant + effluent + substrate + fertilizer prills) ÷ nitrogen inputs

[w] NUE = {plant adsorbed nutrient (mg) ÷ [applied nutrient (mg) – nutrient remaining in CRF prill – nutrient remaining in substrate]} * 100

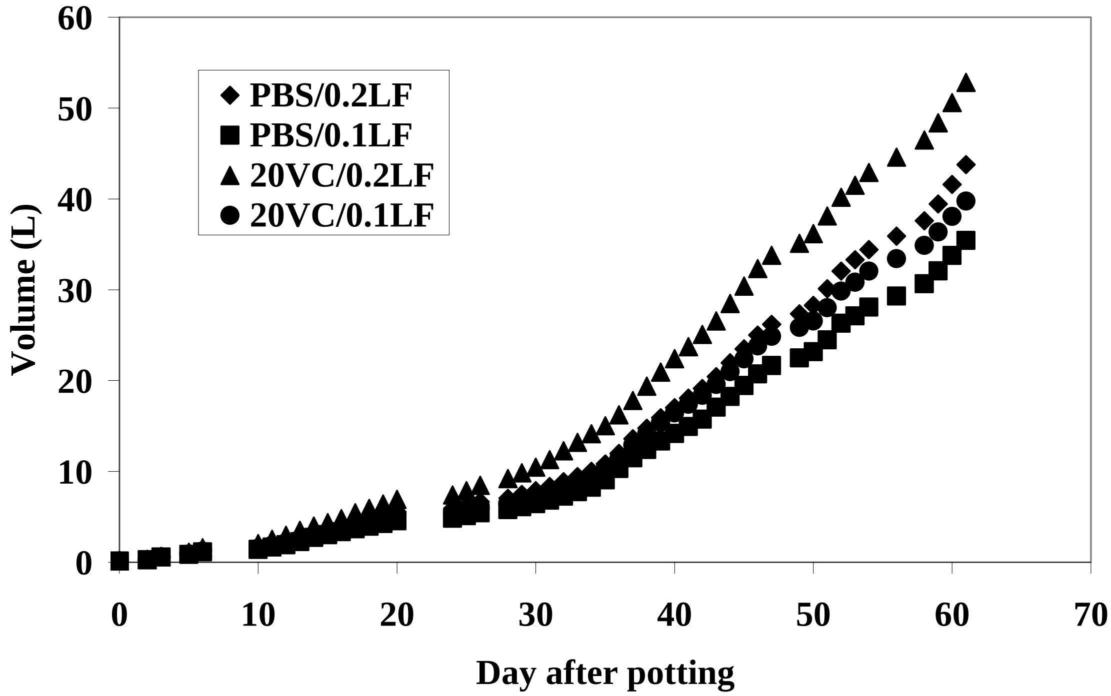

Figure 1. Effect of substrate [PBS = 8 pine bark : 1 sand (v/v); 20VC = pine bark amended with 20% vermicompost (by vol.)] and leaching fraction (LF = vol. applied ÷ vol. leached) on cumulative irrigation water influent per 3.8 L container.

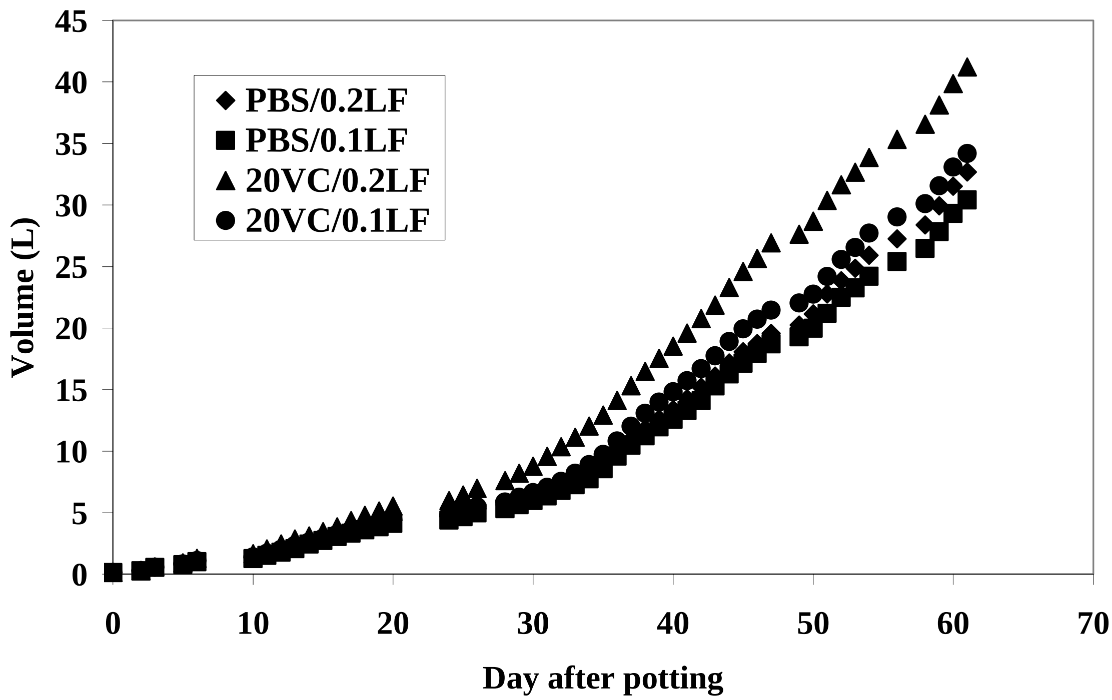

Figure 2. Effect of substrate [PBS = 8 pine bark : 1 sand (v/v); 20VC = pine bark amended with 20% vermicompost (by vol.)] and leaching fraction (LF = vol. applied ÷ vol. leached) on cumulative irrigation water retained per 3.8 L container.

Chapter 5

Replacing conventional nursery crop nutrient inputs with vermicompost for container production of *Hibiscus moscheutos* L. 'Luna Blush'

(In the format appropriate for submission to HortScience)

Replacing conventional nursery crop nutrient inputs with vermicompost for container production of *Hibiscus moscheutos* L. 'Luna Blush'.

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Received for publication _____________. This research was funded in part by the North Carolina Agricultural Research Service (NCARS), Raleigh, NC 27695-7643 and the Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Fellowship. Use of trade names in this publication does not imply endorsement by the NCARS or EPA of products named nor criticism of similar ones not mentioned. Appreciation is extended to William M. Reece and Mary Lorscheider for technical assistance and Cavelle Brownie for statistical assistance. From a thesis submitted by M.S.M. in partial fulfillment of the requirements for the PhD degree.

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Subject Category: Soil Management, Fertilization, and Irrigation

Replacing conventional nursery crop nutrient inputs with vermicompost for container production of *Hibiscus moscheutos* L. 'Luna Blush'.

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Additional index words: hog manure, worm castings, herbaceous perennial, pH.

Abstract. The objectives of this study were to determine which conventional nursery crop inputs could be replaced by vermicompost (VC) for production of *Hibiscus moscheutos* 'Luna Blush' L. (hibiscus). Hibiscus was grown in 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.) derived from swine waste (20VC). Plants were topdressed with one of three controlled release fertilizers; nitrogen (N) only; 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). PBS+NPK served as the industry standard supplied with conventional nursery crop nutrient inputs. Hibiscus plants were grown outdoors on a gravel floor underlain with corrugated plastic for leachate (effluent) collection. An average leaching fraction (LF = volume leached ÷ volume applied) of 0.24 was maintained for all

treatments. Total nutrient plant content was determined by summing the nutrient content by plant partition (root, stem, leaf, and flower bud). Daily inorganic nitrogen (IN-N) and dissolved reactive phosphorus (DRP) effluent contents were determined. Plants were harvested at 35 and 56 days after potting (DAP). Total plant nutrient contents of P, calcium (Ca), magnesium (Mg), and sulfur (S), were greater for all three VC treatments compared to PBS+NPK; and iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) were equivalent or greater for all VC treatments compared to PBS+NPK at 35 and 56 DAP. Thus, this source of VC can replace conventional nutrient inputs for these nutrients. Total plant K content of 20VC+NPK, 20VC+NK, and PBS+NPK was greater than 20VC+N. This source of VC does not provide equivalent K available for plant uptake as conventional nursery crop nutrient inputs. Regardless of lower K in the 20VC+N treatment, all three VC treatments had equivalent total plant dry weight, and all three VC treatments had 58% and 40% greater plant dry weight than PBS+NPK at 35 and 56 DAP, respectively. The three VC treatments had similar IN-N and DRP effluent content, and the three VC treatments had 4.3x more IN-N effluent content and 59x DRP effluent content than PBS+NPK.

Vermicompost is compost produced when earthworms stabilize organic waste materials during a non-thermophillic, aerobic process (Edwards, 1995). The amendment of VC to soilless substrates has been shown to improve plant growth (Atiyeh et al., 2001; Hidalgo and Harkess, 2002), flower production (Hidalgo and Harkess, 2002), and water use efficiency of production (McGinnis et al., 2005) and to provide liming equivalencies (McGinnis, 2007) and 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.) while providing sufficient plant nutrients via a fertilizer. Hidalgo and Harkess (2002) reported increased growth and flower production of 10-week-old chrysanthemum [*Dendranthema x grandiflora* (Ramat.) Kitam. 'Miramar'] grown in VC amended peat moss (PM) based substrate, compared to an unamended PM control, when a complete liquid fertilizer [300 $mg{\cdot}L^{-1}$ nitrogen (N)] was applied to all treatments. Similarly, 3-week-old tomato (*Lycopersicon esculentum* Mill.) seedlings were larger when grown in VC amended PM substrates compared to a PM control (0% VC), even when a complete liquid fertilizer (200 $mg{\cdot}L^{-1}$ N) was applied to all treatments (Atiyeh et al., 2001). Atiyeh et al. (2002) and Bachman and Davis (2000) have reported similar findings with 121-day-old marigold (*Tagetes patula* L. 'Queen Sophia') and 112 day old *Magnolia virginiana* L. liners, respectively. Since sufficient fertilizer nutrients were provided, the Sprengel-Leibig's law of the minimum (Epstein and Bloom, 2004) would suggest that additional nutrients provided by VC were not responsible for increased plant growth. The exact mechanism which causes increased plant growth associated with VC is unclear, however, several researchers have suggested it may be due to synergistic effects of a variety of factors, including improved substrate physical properties, influence of hormone-like substances and humic substances and/or the presence of beneficial microorganisms (Arancon et al., 2004; Tomati and Galli, 1995).

The plant available nutrients associated with VC can benefit containerized crop production systems by reducing fertilizer nutrient inputs from conventional sources. Handreck (1986) reported VC derived from eight sources provided sufficient P, calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo) for production of 59 day old *Matthiola incana* L. (stock), thus inputs of these nutrients from other sources could be eliminated. Handreck found the ability of VC to provide sufficient K and sulfur (S) depended on the waste material from which the VC was derived; and regardless of the VC source sufficient N was not provided by any source. McGinnis (2007) reported a 20% VC (by vol.) amended pine bark (PB) substrate provided plant available N of ~250 mg per 3.8 L container over 6 weeks, which is less than 10% of a common CRF input of 3 g N per 3.8 L container. Thus, it appears VC will not provide sufficient N to maximize containerized crop production and an additional N source will be required.

We hypothesized PB amended with VC derived from hog (*Sus* sp.) 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 inputs could be replaced by vermicompost (VC) for production of *Hibiscus moscheutos* L. ‘Luna Blush’ (hibiscus). Plants were grown with four nutrient input treatments: (1) nutrient inputs that represent standard industry production practices (all macro and micronutrients provided), (2) 20% VC plus N, P, and K, (3) 20% VC plus N and K, and (4) 20% VC plus N. Dry weight and nutrient content of plant partition (root, stem, leaf, flower bud, and total) of plants grown in each treatment were compared.

Materials and Methods

Substrate chemical properties. Samples of VC were collected and submitted to the N.C. Department of Agriculture and Consumer Services (NCDA & CS), Agronomic Division, Raleigh for total nutrient analysis, available phosphorus (P), cation exchange capacity (CEC), electrical conductivity (EC), and pH (Table 1). Prior to analysis, samples were dried at 65^{o}C and ground with a stainless steel grinder (ED-5 Wiley Mill; Thomas Scientific, Swedesboro, N.J.) through a 1 mm screen (Campbell and Plank, 1992). Total carbon (C) and N concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500; CE Elantech Instruments, Milan, Italy) (Campbell, 1992). Total P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and sodium (Na) concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Wellesley, Mass.), following open-vessel HNO_3 digestion in a microwave digestion system (CEM Corp.; Matthews, NC) (Donohue and Aho, 1992). Available P was determined by a Mehlich-3 extractant using ICP (Mehlich, 1984). Electrical conductivity was determined using a 1 substrate : 2 distilled water extract, and pH was determined using a 1 substrate : 1 distilled water extract. Cation exchange capacity was determined by summation of basic cations (excluding Na) and buffer acidity (Mehlich et al., 1976).

Experimental design, substrates, fertilizers, and treatments. The study was a randomized complete block design with four treatments, four blocks, and seven plants per plot.

Substrates included milled PB (<1.25 cm, aged 1 year) amended with 20% VC (v/v) (NatureWorks Organics, Advance, NC) derived from hog manure (hereafter referred to as 20VC) and PB amended with 11% sand (by vol.), 1.8 $kg \cdot m^{-3}$ dolomitic limestone, and 0.9 $kg \cdot m^{-3}$ Micromax® (Scotts, Marysville, OH) (hereafter referred to as PBS). Substrates were blended with a 0.76 m^{-3} rotary mixer (Bouldin & Lawson, LLC, McMinnville, Tenn). The controlled release fertilizers (CRF) formulated by Harrell's Fertilizer Inc. (Lakeland, FL) were 17N-2.4P-10K (17-6-12, 3-4 mo., 12.3% urea, 3.4% nitrate, 1.3% ammonia) (hereafter referred to as NPK), 17N-0P-10K (17-0-10, 3-4 mo., 13.6% urea and 3.4% nitrate) (hereafter referred to as NK), and 17N-0P-0K (17-0-0-, 3-4 mo, 17% urea) (hereafter referred to as N). The four treatments yielded from the substrates and fertilizer combinations are as follows: 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK. Fertilizers were applied as a top dressing at a rate of 5 g N per 3.8-L (29.4 g fertilizer per container). Treatment PBS+NPK served as an industry standard receiving conventional nursery crop nutrient inputs.

Plant material, nutrients, and irrigation. On 22 May 2006, seed propagated *Hibiscus moscheutos* L.'Luna Blush' (hibiscus) transplants obtained from Ball Seed Co., (Chicago, Ill.) were potted into 3.8 L black containers, placed on 16 separate plots at the Horticulture Field Lab at N.C. State Univ., Raleigh and topdressed with CRF. Each gravel covered plot (8 x 1 m) was underlain with corrugated plastic at a 2% slope which directed all leachate from each plot to a 19 L collection vessel. For one plant per plot, CRF was divided into two half-ellipse shaped bags (15.9 cm x 5.8 cm) made from mosquito mesh (No-See-Um Mosquito Net; REI, Sumner, Wash.; Catalog Number 601044) and placed on the substrate surface (to simulate top dressing) for quantification of nutrients remaining in the CRF at the study termination. The available N provided by 20% VC substrates was 305 mg N per 3.8-L container as determined by nutrient release equations developed by McGinnis (2007). The available P provided by 20% VC substrates was estimated to be 254 mg P per 3.8-L (determined by Melich-3 P concentrations).

Irrigation was applied via pressure compensated spray stakes (Acu-Spray Stick; Wade Mfg. Co., Fresno, Calif.; 200 $ml \cdot min^{-1}$) 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, and 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 the 19 L leachate vessels at each plot. Influent volumes were adjusted daily to maintain the LF for each plot. Data were compiled to determine cumulative influent volume per container (L) and cumulative effluent volume per container (L). Cumulative volume water retained per container (L) was calculated as the sum of the daily difference between influent and effluent volumes per container. Water use efficiency of productivity (WUE_p) was calculated according to the following equation: WUE_p ($mL \cdot g^{-1}$) = cumulative volume water retained by the substrate at day of harvest ÷ total plant dry mass. Effluent volumes were measured following rain events with <0.64 cm of rain, however, data collected on these days were not used in the cumulative influent and effluent calculations. A total of 31.8 cm of rain fell on 17 separate days during the study resulting in 8 days of data not included in cumulated totals.

Plant growth and nutrient content. On 23 June 2006 [35 days 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) prior to obtaining dry weights of all segregated parts. Prior to the final harvest date, dates and number of open flowers were recorded for each plant and removed upon senescence (within 24 hours). From the dry weigh data, the following variables were calculated: total dry weight (g) = root dry weight + stem dry weight + leaf dry weight + flower bud dry weight, root weight ratio (RWR) ($g \cdot g^{-1}$) = root dry weight ÷ total dry weight, leaf weight ratio (LWR) ($g \cdot g^{-1}$) = leaf dry weight ÷ total dry weight, and stem weight ratio (SWR) ($g \cdot g^{-1}$) = stem dry weight ÷ total dry weight.

All tissues were ground separately via a Foss Tecator Cyclotec™ 1093 sample mill (Cyclotec) (Analytical Instruments, LLC, Golden Valley, Minn.) to pass ≤ 0.5 mm sieve. Stem and roots were ground initially with a Model 4 bench, 1HP Wiley Mill (Thomas Scientific, Swedensboro, N.J.) to pass through a ≤ 6 mm sieve before passing through the Cyclotec. Tissue samples were analyzed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and B by the NCDA & CS, Agronomic Division, by methods described previously.

Nutrient budget, effluent content, and nutrient use efficiency (N and P). A nutrient budget was developed for each treatment to quantify the 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 + 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 = {plant adsorbed nutrient ÷ [(added nutrient by CRF and VC) – (nutrient remaining in CRF + nutrient remaining in substrate)]} * 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 ammonia (NH_4-N) and nitrate (NO_3-N), and P was quantified as dissolved reactive P (DRP). Inorganic N (IN-N) was calculated as the sum of NH_4-N and NO_3-N.

Nutrients remaining in the substrate at 56 DAP were extracted using a 1 : 3 extract ratio (30 cc substrate : 90 ml DI water), shaken for 1 hour, and filtered through a Whatman #2 filter (Whatman, Inc., Florham Park, N.J.). Nutrients remaining in the CRF were determined by blending CRF prills remaining in the nylon mesh bags at 61 DAP with DI water for 1 min and filtering through 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 NH_4-N, NO_3-N, and DRP.

Statistical analysis. All variables were analyzed using Proc ANOVA in SAS version 9.01 (SAS Inst. Inc., Cary, NC). Treatment comparisons were made by Fisher's Protected *LSD*, $P = 0.05$.

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 VC 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 an addition supply of K resulted in less root growth compared to 20VC treatments to which K was 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.

At 35 DAP no differences in carbon allocation measures were detected between any treatments, RWR (mean = 0.27 ± 0.01), LWR (mean = 0.54 ± 0.01). SWR (mean = 0.19 ± 0.003), and BWR (mean = 0.01 ± 0.002) (data not presented). At 56 DAP, PBS+NPK had the greatest C allocation to root tissue, as indicated by RWR, whereas 20VC+N had the greatest C allocation to leaf tissue, as indicated by LWR (Table 3). Carbon allocation to stem tissue was similar for all treatments, as indicated by SWR. All 20VC treatments had greater carbon allocated to reproductive tissue than PBS+NPK, as indicated by BWR (Table 3).

Irrigation measures. At 35 DAP, WUE_P was similar for 20VC treatments, and all were improved compared to the PBS treatment; however, at 56 DAP, WUE_P was similar for all treatments (Table 2). No differences between treatments were detected at either 35 or 56 DAP for influent per 3.8-L container (mean = 16.2 L ± 0.09 for 35 DAP; mean = 42.6 L ± 1.0 for 56 DAP), effluent per 3.8-L container (mean = 4.5 L ± 0.2 for 35 DAP; 9.9 L ± 0.8 for 56 DAP), or water retained per 3.8-L container (mean = 11.8 mL ± 0.5 for 35 DAP; 32.7 mL ± 0.8 for 56 DAP) (data not presented). The LF averaged 0.24, 0.23, 0.25, and 0.25 for 20VC+NPK, 20VC+NK, 20VC+N and PBS+NPK, respectively.

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 20VC were equivalent or greater than PBS+NPK (Tables 4 and 5). Total plant K content of 20VC+N was less than 20VC+NPK, 20VC+NK, and PBS+NPK, indicating 20VC supplied plant available K at quantities less than that supplied by conventional production practices (Table 4). 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 6). The differences in N content were most likely due to luxury consumption of different amounts of N from CRF and VC available for plant uptake. These data indicate that VC can replace conventional nursery crop nutrient inputs of dolomitic limestone, a micronutrient package, and P in the CRF. Tyler et al. (1993) also reported similar results using a composted turkey litter amended to PB.

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 content, and stem and leaf Mg content. The increased Ca and Mg total content of 20VC+N most likely resulted as a result of reduced competitive uptake inhibition by K. Some physiological roles of K can be replaced by other cations, which may be why decreased plant growth was not observed with 20VC+N treatments (Wyn-Jones, et al., 1979).

Nutrient budget, effluent nutrient content, and nutrient use efficiency (N and P). At 56 DAP, IN-N and DRP effluent content was similar for all three 20VC treatments (Table 6 and 7), and all three VC treatments had an average of 4.3x greater IN-N effluent content and 59x greater DRP effluent content than PBS+NPK. These nutrient effluent contents are much greater than those reported by McGinnis (2007) where IN-N and DRP effluent lost by 20VC was 1.2x and 1.7x greater, respectively, than PBS at 0.2 LF. The differences in the amount of nutrient effluent content between the two studies is likely due to the chemical properties of the VC. The VC used in the study reported by McGinnis (2007) had a pH of 6.11 whereas the pH of the VC used in the study herein was 5.11. McGinnis (2007) has shown increased DRP lost to substrate solution with decreasing pH.

The percent total N applied that was recovered in effluent was 4.7%, 4.5%, 4.5%, and 1.1% for 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK, respectively; and percent total P applied that was recovered in effluent was 45%, 156%, 156%, and 1% for 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK, respectively. Of total N and P inputs with CRF and VC, RN_N was 20%, 19%, 20% and 14% and RN_P was 79%, 265%, 282% and 16% for 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK, respectively (Table 6 and 7). Obviously, the available P determined by the Mehlich-3 analytical procedure underestimated the P available from VC amended to PB resulting in a greater than 100% recovery. Of the RN_N content, 59%, 57%, 72%, and 63% was in plant tissue, 16%, 15%, 0%, and 22% was in the fertilizer, 2%, 5%, 5%, and 7% was in the substrate, and 23%, 23%, 23%, and 8% was in the effluent for 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK, respectively. Of the RN_P content 24%, 27%, 26%, and 39% was in plant tissue, 8%, 0%, 0%, and 51% was in the fertilizer, 11%, 14%, 15%, and 4% was in the substrate, and 57%, 59%, 59%, and 6% was in the effluent for 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK, respectively. NUE_N for 20VC+NPK, 20VC+NK, 20VC+N, and PBS+NPK was 12%, 11%, 15%, and 9%, respectively. The NUE_N reported herein are similar to that reported by Lea-Cox and Ristvey (2003). The NUE_P for treatments receiving a conventional P fertilizer inputs (PBS+NPK and 20VC+NPK) was similar to that reported by Lea-Cox and Ristvey (2003) and Owen (2005).

In summary, VC amended to PB at 20% provided sufficient quantities of plant available nutrients such that an additional supply of P, Ca, Mg, S, and micronutrients need not be added. Thus, the incorporation of dolomitic limestone and a micronutrient package can be eliminated. VC did not supply K in quantities comparable to traditional inputs, however, this reduction of K did not affect growth or flower bud production of hibiscus. Additionally, all three 20VC treatments resulted in greater total plant growth and number of flowers compared to PBS+NPK or the industry standard. However, IN-N and DRP effluent content was much greater from VC treatments. Nutrient loss in effluent could be reduced by eliminating P in the CRF and reducing leaching fractions (Fare et al., 1994; McGinnis, 2007; Owen, 2006; Tyler et al., 1996).

Literature Cited

Arancon, N.Q., C.A. Edwards, A. Atiyeh, and J.D. Metzer. 2004. Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. Bioresource Technol. 93:139-144.

Atiyeh, R.M., N.Q. Arnacon, C.A. Edwards, and J.D. Metzger. 2002. The influence of earthworm-processed pig manure on the growth and productivity of marigolds. Bioresource Technol. 81:103-108.

Atiyeh, R.M., C.A. Edwards, S. Subler, and J.D. Metzger. 2001. Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physiochemical properties and plant growth. Bioresource Technol. 78:11-20.

Bachman, G.R. and W.E. Davis. 2000. Growth of *Magnolia virginiana* liners in vermicompost-amended media. Proc. SNA Res. Conf., Forty-Fifth Annu. Rpt. p. 65-76.

Campbell, C.R. 1992. Determination of total nitrogen in plant tissue by combustion. p. 21-23. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Campbell, C.R. and C.O. Plank 1992. Sample preparation. p. 8-9. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Donohue, S.J. and D.W. Aho. 1992. Determination of P, K, Ca, Mg, Mn, Fe. Al, B, Cu, and Zn in plant tissue by inductively coupled plasma (ICP) emission spectroscopy. p. 37-40. In: C.O. Plank (ed). Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Coop. Series Bull. 368.

Edwards, C.A. June 1995. Historical overview of vermicomposting. BioCycle. 36:50-54.

Epstein, E. and A.J. Bloom. 2005. Mineral nutrition of plants: Principles and perspectives. 2nd. Sinauer Assoc., Sunderland, Mass.

Fare, D.C., C.H. Gilliam, and G.J. Keever. 1994. Cyclic irrigation reduces container leachate nitrate-nitrogen concentration. HortScience 29:1514-1517.

Handreck, K. 1986. Vermicomposts as components of potting media. BioCycle 27:58-62.

Hidalgo, P.R. and R. L. Harkess. 2002. Earthworm castings as a substrate amendment for chrysanthemum production. HortScience 37:1035-1039.

McGinnis, M.S. 2007. Sustainable use of vermicomposted hog waste: The use of worm castings as nursery growing substrates amendment to increase water and nutrient efficiency in containerized nursery plant production. North Carolina State Univ., Raleigh, PhD Diss.

McGinnis, M., T. Bilderback, and S. Warren. 2005. Vermicompost: Improving water use efficiency in nursery crop production. Proc. SNA. Res. Conf. 50:73-77.

Mehlich, A. 1984. Mehlich-3 soil test extractant: a modification of Mehlich-2 extractant. Commun. Soil Sci. Plant anal. 15(12):140916.

Mehlich, A., S.S. Bowling, and A.L. Hatfield. 1976. Buffer pH acidity in relation to nature of soil acidity and expression of lime requirement. Commun. Soil Sci. Plant Anal. 7(3)25363.

Owen, Jr., J.S. 2006. Clay amended soilless substrates: Increase water and nutrient efficiency in containerized crop production. North Carolina State Univ., Raleigh, PhD Diss.

Tomati, U. and E. Galli. 1995. Earthworms, soil fertility, and plant productivity. Acta Zoo. Fennica. 196:11-14.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficacy. J. Environ. Hort. 14:199-204.

Tyler, H.H., S.L. Warren, T.E. Bilderback, and B. Perry. 1993. Composted turkey litter: I. Effect on plant growth. J. Environ. Hort. 11:137-141.

Wyn-Jones, R., C. Brady, and J. Spiers. 1979. Ionic and osmotic relations in plant cells, p63-103. In D. Laydman (ed.). Recent advances in the biochemistry of cereals. Academic Press, London, UK.

Table 1. Initial nutrient concentrations of vermicompost.

N	P	K	Ca	Mg	S	pH	C:N
			$mg \cdot g^{-1}$				
18 ± 2[z]	17 ± 2	1.5 ± 0.2	55 ± 7	2.3 ± 0.3	3.5 ± 0.5	5.6 ± 0.0	8.4 ± 0.1

Fe	Mn	Zn	Cu	B	Na	EC	CEC
			$ug \cdot g^{-1}$			$dS \cdot m^{-1}$	
4333 ± 565	480 ± 45	550 ± 64	112 ± 11	0.2 ± 0.2	571 ± 70	5.5 ± 0.3	61.1 ± 3.1

[z]Means ± 1 SE based on 3 observations.

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

DAP	Substrate[z]	Root dry weight	Stem dry weight	Leaf dry weight	Flower bud dry weight	Total dry weight	Flower number[y]	WUE_p[x]
		g						mL g^{-1}
35	20VC+NPK	4.0 a ± 0.3[vw]	2.7 a ± 0.2	7.4 a ± 0.2	0.15 a ± 0.02	14.2 a ± 0.5	15.3 a ± 3.2	839 b ± 50
	20VC+NK	3.8 a ± 0.3	2.5 a ± 0.2	7.1 a ± 0.6	0.10 a ± 0.02	13.6 a ± 0.8	14.0 a ± 3.6	898 b ± 36
	20VC+N	2.5 b ± 0.2	2.2 a ± 0.1	6.5 a ± 0.4	0.09 a ± 0.05	11.3 b ± 0.6	9.3 a ± 2.6	945 b ± 60
	PBS+NPK	2.3 b ± 0.2	1.5 b ± 0.1	4.3 b ± 0.3	0.10 a ± 0.08	8.2 c ± 0.6	5.5 a ± 1.6	1525 a ± 223
56	20VC+NPK	17.0 a ± 1.8	12.6 a ± 1.0	18.4 a ± 1.0	5.02 a ± 1.03	53.1 a ± 4.2	54.5 a ± 5.8	659 a ± 69
	20VC+NK	16.3 ab ± 0.2	12.6 a ± 0.4	18.1 a ± 0.4	5.55 a ± 0.75	52.5 a ± 1.3	54.6 a ± 3.1	678 a ± 45
	20VC+N	13.3 c ± 0.7	12.7 a ± 0.3	19.6 a ± 0.6	4.41 a ± 0.45	50.1 a ± 1.8	58.4 a ± 4.0	639 a ± 63
	PBS+NPK	13.6 bc ± 0.4	8.8 b ± 0.6	13.3 b ± 0.8	1.49 b ± 0.28	37.2 b ± 1.6	28.9 b ± 5.5	818 a ± 90

[z]PBS = 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.

[y]Flower number = number of senesced flowers removed prior to harvest.

[x]WUE_p (water use efficiency of productivity) = volume of water retained by substrate (mL) ÷ total plant dry weight (g).

[v]Each mean ± standard error is based on 4 observations.

[w]Means within each variable within each DAP followed by the same letter are not significantly different as determined by Fisher's Protected LSD at $P \leq 0.05$

Table 3. Effect of nutrient inputs on carbon allocation measures of *Hibiscus moscheutos* 'Luna Blush' at 56 days after potting (DAP).

DAP	Substrate[z]	RWR[y]	LWR[x]	SWR[w]	BWR[v]
56	20VC+NPK	0.32 b ± 0.02[ut]	0.35 b ± 0.02	0.24 a ± 0.01	0.09 a ± 0.01
	20VC+NK	0.31 b ± 0.00	0.34 b ± 0.01	0.24 a ± 0.00	0.10 a ± 0.01
	20VC+N	0.27 c ± 0.01	0.39 a ± 0.00	0.25 a ± 0.00	0.09 a ± 0.01
	PBS+NPK	0.37 a ± 0.02	0.36 b ± 0.01	0.24 a ± 0.01	0.04 b ± 0.01

[z]PBS = 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.

[y]RWR (root weight ratio) = root weight (g) ÷ total dry weight.

[x]SWR (stem weight ratio) = stem dry weight (g) ÷ total dry weight (g).

[w]LWR (leaf weight ratio) = leaf dry weight (g) ÷ total dry weight (g).

[v]BWR (flower bud weight ratio) = flower bud dry weight (g) ÷ total dry weight (g)

[u]Each mean ± standard error is based on 4 observations.

[t]Means within each variable within each DAP followed by the same letter are not significantly different as determined by Fisher's Protected LSD at $P \leq 0.05$

Table 4. Effect of nutrient inputs on macronutrient content of *Hibiscus moscheutos* 'Luna Blush' tissues at 56 days after potting.

Tissue	Substrate[z]	N	P	K	Ca	Mg	S
		mg					
Root	20VC+NPK	121 a ± 9[yx]	64 a ± 4	199 a ± 23	101 a ± 10	56 a ± 3	26 a ± 3
	20VC+NK	96 a ± 2	58 ab ± 1	200 a ± 5	98 a ± 4	53 a ± 2	25 a ± 0
	20VC+N	126 a ± 12	49 b ± 3	44 b ± 1	91 a ± 6	50 a ± 2	24 a ± 2
	PBS+NPK	99 a ± 3	16 c ± 1	181 a ± 11	57 b ± 2	54 a ± 1	20 a ± 1
Stem	20VC+NPK	76 b ± 9	35 a ± 3	159 ab ± 6	165 b ± 14	30 b ± 3	11 b ± 1
	20VC+NK	61 b ± 3	33 a ± 2	172 a ± 11	159 b ± 9	26 b ± 1	11 b ± 0
	20VC+N	108 a ± 9	36 a ± 1	40 c ± 1	211 a ± 9	56 a ± 1	13 a ± 1
	PBS+NPK	64 b ± 6	9 b ± 1	141 b ± 9	61 c ± 5	25 b ± 3	7 c ± 0
Leaf	20VC+NPK	332 b ± 23	69 b ± 6	244 b ± 15	540 b ± 36	93 b ± 7	31 a ± 3
	20VC+NK	291 bc ± 13	69 b ± 2	257 b ± 18	526 b ± 13	86 b ± 3	32 a ± 2
	20VC+N	417 a ± 18	86 a ± 4	68 c ± 2	722 a ± 35	148 a ± 3	35 a ± 0
	PBS+NPK	257 c ± 17	16 c ± 2	338 a ± 26	215 c ± 12	78 b ± 9	24 b ± 2
Flower Bud	20VC+NPK	174 a ± 35	29 a ± 7	138 a ± 33	114 a ± 26	30 a ± 7	12 a ± 3
	20VC+NK	176 a ± 10	30 a ± 2	149 a ± 10	122 a ± 6	32 a ± 1	13 a ± 0
	20VC+N	155 a ± 19	24 a ± 2	59 b ± 4	108 a ± 9	25 a ± 1	11 a ± 1
	PBS+NPK	40 b ± 7	3 b ± 1	32 b ± 5	18 b ± 4	8 b ± 2	3 b ± 0
Total	20VC+NPK	630 ab ± 53	184 a ± 15	680 a ± 54	870 b ± 64	195 b ± 12	75 a ± 7
	20VC+NK	581 bc ± 54	182 a ± 10	741 a ± 48	874 b ± 48	189 b ± 7	78 a ± 4
	20VC+N	768 a ± 76	190 a ± 10	196 b ± 13	1105 a ± 69	272 a ± 9	80 a ± 4
	PBS+NPK	436 c ± 19	43 b ± 2	673 a ± 30	341 c ± 11	160 c ± 10	51 b ± 3

Table 4. Continued

[z]PBS = 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.

[y]Each mean ± standard error is based on 4 observations.

[x]Means within each variable within each DAP followed by the same letter are not significantly different as determined by Fisher's Protected LSD at $P \leq 0.05$.

Table 5. Effect of nutrient inputs on micronutrient content of *Hibiscus moscheutos* 'Luna Blush' tissues at 56 days after potting.

Tissue	Substrate[z]	Fe	Mn	Zn	Cu	B
		ug				
Root	20VC+NPK	1605 a ± 172	802 b ± 58	1670 b ± 76	230 b ± 19	242 a ± 19
	20VC+NK	1556 a ± 152	713 b ± 16	1669 b ± 71	208 b ± 12	244 a ± 6
	20VC+N	1360 a ± 165[yx]	727 b ± 51	1959 a ± 65	197 b ± 7	201 a ± 9
	PBS+NPK	1794 a ± 174	1174 a ± 43	1210 c ± 52	308 a ± 7	215 a ± 3
Stem	20VC+NPK	464 a ± 43	571 b ± 58	576 a ± 38	114 a ± 9	218 a ± 18
	20VC+NK	538 a ± 59	566 b ± 31	528 a ± 27	102 a ± 6	232 a ± 14
	20VC+N	471 a ± 18	672 b ± 26	595 a ± 20	119 a ± 5	230 a ± 5
	PBS+NPK	347 b ± 26	868 a ± 95	404 b ± 35	96 b ± 8	168 b ± 13
Leaf	20VC+NPK	3933 a ± 1713	4493 a ± 248	1996 a ± 123	162 a ± 14	555 a ± 20
	20VC+NK	6448 a ± 2260	4372 a ± 141	1867 a ± 67	168 a ± 13	542 a ± 19
	20VC+N	1404 a ± 43	5525 a ± 302	1783 a ± 57	157 a ± 5	571 a ± 15
	PBS+NPK	2945 a ± 997	5371 a ± 394	1702 a ± 160	127 a ± 11	481 a ± 24
Flower Bud	20VC+NPK	328 ab ± 77	864 a ± 211	357 a ± 78	111 a ± 21	157 a ± 32
	20VC+NK	403 a ± 36	850 a ± 14	399 a ± 18	126 a ± 11	178 a ± 14
	20VC+N	250 bc ± 11	753 a ± 67	271 a ± 21	97 a ± 6	147 a ± 14
	PBS+NPK	155 c ± 36	351 a ± 70	89 a ± 12	47 b ± 9	38 b ± 6
Total	20VC+NPK	6189 a ± 1673	6354 a ± 474	4445 a ± 179	569 a ± 42	1106 a ± 72
	20VC+NK	8844 a ± 2960	6289 a ± 305	4363 a ± 191	572 a ± 57	1151 a ± 60
	20VC+N	3422 a ± 129	7489 a ± 438	4540 a ± 81	546 a ± 36	1112 a ± 46
	PBS+NPK	5148 a ± 1065	7553 a ± 429	3352 b ± 210	550 a ± 16	879 b ± 28

Table 5. Continued

[z]PBS = 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.

[y]Each mean ± standard error is based on 4 observations.

[x]Means within each variable within each DAP followed by the same letter are not significantly different as determined by Fisher's Protected LSD at $P \leq 0.05$.

Table 6. Nitrogen partition of *Hibiscus moscheutos* 'Luna Blush' grown with different nutrient inputs at 56 days after potting.

Nitrogen partition	20VC+NPK^z	20VC+NK^z	20VC+N^z	PBS+NPK^z
Inputs				
Fertilizer (mg)	5000	5000	5000	5000
Vermicompost (mg)	305	305	305	0
Outputs				
Effluent NO_3-N (mg)	233 a	227 a	222 a	48 b
Effluent NH_4-N (mg)	15 a	14 ab	17 a	9 b
Hibiscus (mg)	630	581	768	436
Remaining in system				
Substrate NO_3-N (mg)	12.6	29.1	6.0	40.3
Substrate NH_4-N (mg)	11.7	22.9	49.3	9.6
Fertilizer NO_3-N (mg)	126.0	147.8	0.2	122.3
Fertilizer NH_4-N (mg)	36.9	1.3	1.7	34.1
RN_N^y (mg)	1065	1023	1064	699
RN_N^x (%)	20	19	20	14
NUE_N^w (%)	12	11	15	9

^{z}PBS = 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.

^{y}RN_N (mg) = N in plant + effluent + substrate + fertilizer prills.

^{x}RN_N (%) = (N in plant + effluent + substrate + fertilizer prills) ÷ nitrogen inputs

^{w}NUE_N = {plant adsorbed nutrient (mg) ÷ [applied nutrient (mg) – nutrient remaining in CRF prill – nutrient remaining in substrate]} * 100

Table 7. Phosphorus partition of *Hibiscus moscheutos* 'Luna Blush' grown with different nutrient inputs at 56 days after potting.

Phosphorus partition	20VC+NPK[z]	20VC+NK[z]	20VC+N[z]	PBS+NPK[z]
Inputs				
Fertilizer (mg)	706	0	0	706
Vermicompost (mg)	254	254	254	0
Outputs				
Effluent (mg)	430 a	395 a	421 a	7 b
Hibiscus (mg)	184	182	190	43
Remaining in system				
Substrate (mg)	83.0	96.7	104.5	4.2
Fertilizer prills (mg)	58.8	0.0	0.1	55.3
RN_P (mg)	756	674	716	110
RN_P (%)	79	265	282	16
NUE_P (%)	23	116	127	7

[z]PBS = 8 pine bark : 1 sand with 1.8 $kg{\cdot}m^{-3}$ dolomitic limestone and 0.9 $kg{\bullet}m^{-3}$ 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.

[y]RN_P (mg) = P in plant + effluent + substrate + fertilizer prills.

[x]RN_P (%) = (P in plant + effluent + substrate + fertilizer prills) ÷ nitrogen inputs

[w]NUE_P = {plant adsorbed nutrient (mg) ÷ [applied nutrient (mg) – nutrient remaining in CRF prill – nutrient remaining in substrate]} * 100