HORTSCIENCE 47(3):395–402. 2012.

Pak Choi (*Brassica rapa*, Chinensis Group) Yield, Phytonutrient Content, and Soil Biological Properties as Affected by Vermicompost-to-water Ratio Used for Extraction

Archana P. Pant, Theodore J.K. Radovich[1], Nguyen V. Hue, and Susan C. Miyasaka

Department of Tropical Plant and Soil Sciences, University of Hawai'i, 3190 Maile Way, Honolulu, HI 96822

Additional index words. compost tea, total glucosinolates, total phenolics, total carotenoids, dehydrogenase activity

***Abstract*. Previous work has demonstrated the potential of compost tea to enhance plant growth and nutritional status. One factor thought to contribute to variability in the efficacy of compost tea is the amount of compost per unit volume of water. To address these gaps in our understanding, two greenhouse trials and two field trials were conducted to investigate the effects of various extraction ratios on the growth, mineral nitrogen (N), and phytonutrient content of pak choi (*Brassica rapa,* Chinensis) and on soil biological properties. In greenhouse experiments, plants were fertilized with a single rate of chicken manure-based thermophilic compost. In field trials, three fertilizer treatments: 1) rendered meat byproduct or Tankage (Island Commodities, Honolulu, HI); 2) soluble fertilizer (16:16:16); and 3) chicken manure-based thermophilic compost were applied. Aerated vermicompost teas were prepared using chicken manure-based vermicompost and water at various ratios. Pak choi plants were treated weekly for 4 weeks with 10%, 5%, 3%, and 1% vermicompost teas in the greenhouse experiments and 10% and 5% teas in the field trials. Applications of vermicompost tea significantly increased plant growth, N content, total carotenoids, and total glucosinolates in plant tissue; this response was greatest in chicken manure-fertilized treatments. Increases in yield and phytonutrient content were associated with increased N uptake. Vermicompost tea also increased soil respiration and dehydrogenase activity over the control (water). Plant growth, phytonutrient content, and microbial activities in soil increased with increasing concentrations of vermicompost tea. Within the range of concentrations evaluated (1%–10%), greatest plant growth response was observed with 5% and 10% vermicompost tea, indicating that the optimal water-to-vermicompost ratio for extraction is lower than 50:1 and is likely in the range of 10:1 to 20:1. The findings suggest that vermicompost tea could be used to improve plant nutrient status and enhance soil biological properties in vegetable production.**

Vegetable growers have long used aqueous extracts of compost to extend the benefits of relatively small amounts of material over large areas without incorporation. This strategy is designed to reduce costs associated with compost production, transportation, and application, and the popular literature has documented ample anecdotal reports of the value of compost extracts to promote plant growth (Diver, 2001; Ingham, 2005; Kannangara et al., 2006; Merrill and McKeon, 2001). Unfortunately, limited evaluations of these claims have been published in the refereed literature to date. However, there is growing body of evidence demonstrating application of compost tea as an option for conventional and organic growers to improve plant growth and nutrient quality, enhance soil biological properties, and suppress plant diseases (Pant et al., 2009; Scheuerell and Mahaffee, 2004; Zaller, 2006).

Currently, there is a need for investigation on variability of effectiveness of vermicompost tea application. Several factors can influence the efficacy of vermicompost tea applications to elicit measurable responses in plants. Previous work has demonstrated that vermicompost extracted with or without active aeration can increase yield and carotenoid content in pak choi and the effect has been confirmed in multiple soil types (Pant et al., 2011, 2009).

Dilution rate (i.e., ratio of compost to water) has been identified as a primary factor contributing to variability in tea effect. Studies on the effect of compost tea dilution have mainly focused on disease suppression with diverse results. Palmer et al. (2010) reported that the disease suppression effect of compost tea was greater at 33% (1:2 compost to water ratio, v:v), 10% (1:10, v:v), and 3% (1:33, v:v) dilution rates of aerated compost tea compared with a lower dilution rate of 50% (1:1, v:v) or a much greater dilution rate of 1% (1:100, v:v) tea. Welke (2005) confirmed that strawberry plants receiving 12.5% dilution rate (1:8, v:v) compost tea had higher yield and lower incidence of disease compared with the plants treated with 25% dilution rate (1:4, v:v) tea. Scheuerell and Mahaffee (2004) also reported that application of 3% dilution rate (1:30, v:v) vermicompost tea had a greater effect on suppression of cucumber damping-off caused by *Pythium ultimum* compared with the much greater dilution rate of 0.4% dilution rate (1:270, v:v) vermicompost tea. Weltzien (1990) reported that the effects of 33% and 10% dilution rates of compost tea on suppression of *Phytopthora infestans* was greater than that of the much greater dilution rate of 2% tea. No difference in suppression was observed between 33% and 10% dilution rates of tea.

The absence of systematic evaluation of compost extract concentrations on the response of plant growth is a particularly conspicuous deficit in the literature. In addition to contributing to the general body of knowledge, filling this gap in our understanding is expected to improve the productivity of growers who wish to use compost tea. We hypothesized that vermicompost tea concentration would alter the effects of the extract on plant growth and nutritive quality as well as soil biological properties. The objectives of this study were to determine the effects of concentrations of vermicompost tea on: 1) yield, mineral nutrient concentration, and phytonutrient content of pak choi; and 2) soil biological properties.

Materials and Methods

Greenhouse experiments

Greenhouse experiments were conducted twice at the Magoon Research Facility (lat. 21°18′22″ N, long. 157°48′37″ W) of the University of Hawaii to determine the effects of concentrations of vermicompost tea on plant growth. Pak choi plants were grown in peat–perlite medium fertilized with chicken manure-based thermophilic compost to provide 75 mg N/L growth media (≈150 kg N/ha). Plants were grown in garden pots (volume: 865 cm^3). Three to four pak choi seeds were sown into each pot. Two d after seedling emergence in all pots, plants were thinned to one plant/pot. Plants were allowed to grow in the greenhouse on a bench fitted with overhead sprinklers with a frequency of every 4 h for 5 min throughout the experiments. Aerated vermicompost tea was prepared by extracting commercially produced chicken manure-based vermicompost in water at 1:10 dilution rate (vermicompost-to-water ratio by volume and referred as 10% vermicompost tea) with

Received for publication 7 Oct. 2011. Accepted for publication 2 Jan. 2012.
This research has been funded by Western SARE and TSTAR grants.
We acknowledge Drs. Robert E. Paull, Norman Arancon, and Brent Sipes for internal review of the manuscript and Drs. Travis Idol and J.P. Bingham for granting us access to their laboratories.
[1]To whom reprint requests should be addressed; e-mail theodore@hawaii.edu.

continuous aeration for 12 h (Pant et al., 2009). This extract was further diluted with water to produce 5%, 3%, and 1% dilution ratios. These four dilution rates of extract (referred as 10%, 5%, 3%, and 1% vermicompost tea) and the same amount of aerated water (control) were applied for 4 weeks starting at 5 d after seedling emergence to the root zone and foliage of plants at the rate of 150 mL/pot in each application event. Half of the tea was applied to the root zone and the remaining half was applied to the foliage; however, the tea applied to the foliage moved to the root zone once the foliage was saturated. The teas were prepared in separate events for every week of application. The experiments were arranged in a completely randomized design with five vermicompost tea treatments and six replications per treatment.

Plants were harvested at 5 weeks after emergence. Fresh weight, dry weight, and plant height were measured. Total root length and surface area of the roots of pak choi plants grown in greenhouse experiments were calculated using WinRHIZO Pro V. 2003b system (Regent Instruments Inc., Quebec, Canada). The system consists of a scanner and WinRHIZO software. The fresh weights of roots were recorded, then roots were placed in an oven at 70 °C for 72 h, and then dry weight of roots was recorded.

Field experiments

The field research was located at two sites.

Site A: Waimanalo Research Station. Waimanalo Research Station of the College of Tropical Agriculture and Human Resources, University of Hawaii, Oahu (lat. 21°20′41″ N, long. 157°44′31″ W, elevation 20–29 m) has Waialua series soil (Order: Mollisols and Family: very-fine, kaolinitic, isohyperthermic, Vertic Haplustolls). The average daily maximum and minimum temperatures during the experiment were 28 and 23 °C, respectively.

Site B: Poamoho Research Station. Poamoho Research Station of the College of Tropical Agriculture and Human Resources, University of Hawaii, Oahu (lat. 21°32′58″ N, long. 158°05′47″ W, elevation 166–214 m) has Wahiawa series soil (Order: Oxisol and Family: clayey, kaolinitic, isohyperthermic, Tropeptic Eutrustox). The average daily maximum and minimum temperatures during the experiment were 22 and 16 °C, respectively.

Experimental design and transplanting

Experiments were conducted during June to July 2009 at Site A and February to Mar. 2010 at Site B. Three sources of fertilizer were used: 1) Tankage, a commercially produced rendered, dried, and ground meat byproduct that is largely meat and bone from animals (Island Commodities, Honolulu, HI); 2) a chicken manure-based thermophilic compost; and 3) a soluble fertilizer (16:16:16) were used in both sites to provide 150 kg N/ha. Plant-available N for Tankage and chicken manure-based thermophilic compost was calculated based on total N content with an estimate of 50% mineralization rate during the growth period. All fertilizers were incorporated into the top 15 cm of the raised bed of soil.

Drip irrigation systems were set up after fertilizer applications. Three subplots that measured 1 m × 2.1 m were randomly assigned using three vermicompost tea treatments. Three-week-old pak choi (*Brassica rapa,* Chinensis) seedlings were transplanted in three rows with 21 plants/plot. Aerated vermicompost teas were prepared by extracting commercially produced chicken manure-based vermicompost in water at 1:10 and 1:20 dilution rates (vermicompost-to-water ratio by volume and referred as 10% and 5% vermicompost tea, respectively) with continuous aeration for 12 h (Pant et al., 2009). The control treatment consisted of the same amount of water as the vermicompost tea extracts. These three tea treatments were applied weekly starting a week after transplanting at the rate of 150 mL/transplant for 4 weeks wetting the root zone and foliage of the plants. Compost teas were applied with a small watering can to maintain the uniformity on tea application. The experiments were arranged in randomized complete block design with 3*3 factorial treatments (fertilizer × vermicompost tea treatments) and four blocks of each treatment combination.

Analysis of vermicompost tea

The pH and electrical conductivity (EC) of the vermicompost extracts were measured using a conductivity/pH Meter (SB80PC, sympHony; VWR Scientific Products, MN). Dissolved oxygen (DO) was recorded at 21–22 °C with a dissolved oxygen meter (thermo sympHony SP70D; VWR Scientific Products). Mineral nutrients in vermicompost teas were analyzed in the Agricultural Diagnostic Service Center, University of Hawaii at Manoa. Mineral N (NH_4-N, NO_3-N, and NO_2-N) of the vermicompost tea was analyzed colorimetrically using a discrete analyzer (Easy Chem Plus; Systea Scientific, IL). Other nutrients of the vermicompost tea were analyzed using an inductively coupled plasma spectrophotometer (Jarrel-Ash Division/Fisher Scientific Co., Waltham, MA). Humic acids from vermicompost tea were extracted using the alkali/acid fractionation procedure as described by Valdrighi et al. (1996).

Plant harvest and measurement

Three whole plant samples from Site A and five from Site B were selected randomly from the center row and harvested 5 weeks after transplanting from each treatment. Fresh weight, plant height, and stem basal diameter were measured. Plants were immediately frozen in liquid N and stored at –20 °C and then freeze-dried using a lyophilizer (D4A; Leybold-Heraeus Vacuum Products, Inc., PA). Aboveground dry weight of each plant was recorded, ground using a mortar and pestle, and stored in airtight containers before further analysis.

Measurement of phytonutrients and tissue nitrogen

Total carotenoids and total phenolics were analyzed on lyophilized samples of each treatment by extracting 100 mg in 20 mL of ethanol:acetone (1:1, v:v) in glass vials (Gross, 1991). All data were reported based on the dry weight of the lyophilized sample. Extracts were evaluated for total carotenoids at 470 nm using Genesys 20 spectrophotometer (Model 4001-000; Thermo Scientific, MA). Total carotenoids were calculated according to Gross (1991) using the equation: $mg \cdot L^{-1}$ total carotenoids = $(A*V \times 10^6)/(A\% \times 100G)$, where A is the absorbance, V is the total volume of the extract (mL), A% is the extinction coefficient of 2500, and G is the sample weight in grams. Total soluble phenolics were measured using the Prussian Blue assay as described by Stern et al. (1996) and the data reported in $mg \cdot kg^{-1}$ equivalents of gallic acid. Total glucosinolates were extracted and analyzed from lyophilized samples as described by Radovich et al. (2005). Total N of dried tissue samples was analyzed by dry combustion in a LECO CN-2000 analyzer (Leco Corp., St. Joseph, MI) in the Agricultural Diagnostic Service Center, University of Hawaii at Manoa.

Soil respiration and dehydrogenase activity (Site A)

Soil respiration rate was measured weekly for 4 weeks with a portable soil respiration rate measuring system (LI-6400; LI-COR, Lincoln, NE) fitted with a soil respiration chamber (6400-09; LI-COR). The respiration rate was expressed as $\mu mol\ CO_2$ fluxes/m^2/sec. Dehydrogenase activity in soil was measured as described by Alef (1995). Dehydrogenase activity (expressed in $\mu g \cdot g^{-1}$ of oven-dried soil) was calculated based on the amount of triphenyl formazan formed when 2,3,5-triphenyl tetrazolium chloride was reduced by microbes in the soil.

Statistical analysis

Analysis of variance of plant growth parameters, mineral nutrients, phytonutrients in plant tissue, and soil biological properties was performed using PROC GLM in SAS 9.1 statistical software (SAS Institute Inc., 2003). Trend analysis by polynomial regression was conducted for all plant growth parameters between 0% and 10% vermicompost tea treatments in greenhouse experiments. In field experiments, linear and quadratic effects of vermicompost tea concentration were calculated by polynomial regression for plant growth parameters, mineral nutrients, phytonutrient concentration, and soil biological properties. Fertilizer effect was calculated using orthogonal contrasts. Statistical significance was obtained at a 95% confidence level ($\alpha = 0.05$).

Results

Greenhouse experiments

Application of vermicompost tea significantly ($P < 0.0001$) increased plant biomass, height, leaf area, root length, and root surface area compared with those of the control treatment across both trials. There was a non-significant interaction between tea types and trials on measured growth parameters. Increasing concentration of vermicompost tea increased aboveground dry matter, resulting in a strong (η^2 = 0.79) and significant (P < 0.0001) linear effect (Fig. 1). Quadratic effect was small (η^2 = 0.02) yet significant (P < 0.01), whereas cubic and quartic effects were not significant. Similar trends were observed in height, leaf area, root dry weight, root length, and root surface area (Fig. 2).

Field experiments

Chemical properties of vermicompost and vermicompost teas. The pH of vermicompost was near neutral and its EC was 3.2 dS·m^{-1} with a C:N ratio of 13:1 (Table 1). The average pH of the control treatment was significantly (P < 0.0001) greater than the pH of 10% or 5% tea. The pH of 5% tea was also significantly (P < 0.01) higher than that of 10% tea. The EC levels in both vermicompost tea treatments were significantly (P < 0.0001) greater than that of the control. Also, the EC of 10% tea was significantly higher than that of 5% tea. Dissolved oxygen was significantly (P < 0.0001) lower in both teas compared with the control, but the level of DO was not different between the two concentrations. Humic acid was significantly (P < 0.0001) higher in 10% tea compared with 5% tea. Humic acid was undetectable in the control. The levels of total N, NO_3-N, and NH_4-N were significantly (P < 0.0001) greater in both the teas compared with control. Total N and NO_3-N was significantly (P < 0.05) higher in 10% tea compared with 5% tea but NH_4-N was not influenced by the concentration. Phosphorus concentration in the vermicompost tea was significantly (P < 0.0001) greater in both the tea treatments compared with the control, but it did not differ between the two tea concentrations. Potassium, calcium, and magnesium concentrations followed similar trends with total N. Micronutrient concentrations were significantly (P < 0.05) higher in 10% tea compared with 5% tea and control.

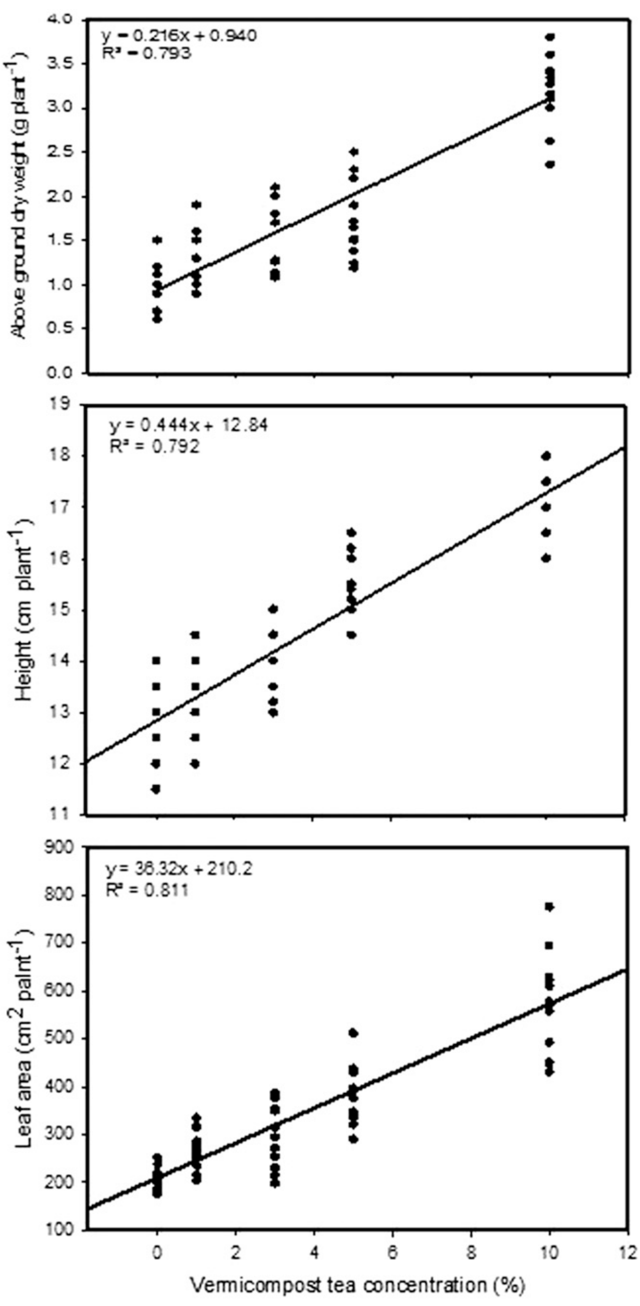

Fig. 1. Effect of vermicompost tea on aboveground plant growth of pak choi in greenhouse trials (n = 60).

Effect on plant growth and tissue nitrogen content (Site A). Application of vermicompost teas significantly increased aboveground plant dry matter, tissue N content, height, and stem basal diameter of pak choi (Table 2). Increasing concentration of vermicompost tea significantly increased aboveground dry weights and heights across all fertilizer types. Significant differences resulting from fertilizer type were found, in which chicken manure resulted in the lowest aboveground dry weights and heights. No significant interactions were found, indicating similar effects of compost teas in three fertilizer treatments.

There was a significant interaction effect of vermicompost tea type and fertilizer type on the aboveground fresh weight (Fig. 3), stem basal diameter, and tissue N content (Table 2), indicating vermicompost tea effect varies with fertilizer type. Aboveground fresh weight and stem basal diameter were unaffected by vermicompost tea concentrations under Tankage treatment, resulting in non-significant linear (P < 0.84) and quadratic (P < 0.839) effects. Increasing concentration of vermicompost tea significantly increased aboveground fresh weight and stem basal diameter in the other two fertilizer treatments, resulting in a significant linear (P < 0.0001) effect. Although there was a significant linear effect of vermicompost tea concentration on tissue N content averaged across all fertilizer types, the effect was stronger in the chicken manure treatment compared with the other two fertilizer treatments.

Effect on phytonutrients (Site A). Increasing concentrations of vermicompost teas significantly increased total carotenoids and total glucosinolates across all fertilizer treatments (Table 2). The effect of vermicompost tea on total phenolics was not significant across all fertilizer treatments and the overall mean was 5778 mg·kg^{-1} (dry weight basis) expressed as gallic acid equivalent. Significant differences resulting from fertilizer type were found for total glucosinolates, in which the soluble fertilizer treatment resulted in the lowest level. Fertilizer had no significant effect on total carotenoids. No significant interactions between vermicompost tea type and fertilizer were found, indicating similar effects of compost teas in the three fertilizer treatments.

Effect on plant growth and tissue nitrogen content (Site B). Application of vermicompost teas significantly increased aboveground plant matter, tissue N content, height, and stem basal diameter of pak choi (Table 3). Increasing concentration of vermicompost teas significantly increased aboveground dry weights, heights, and tissue N content averaged across all fertilizer types. Significant differences resulting from fertilizer type were

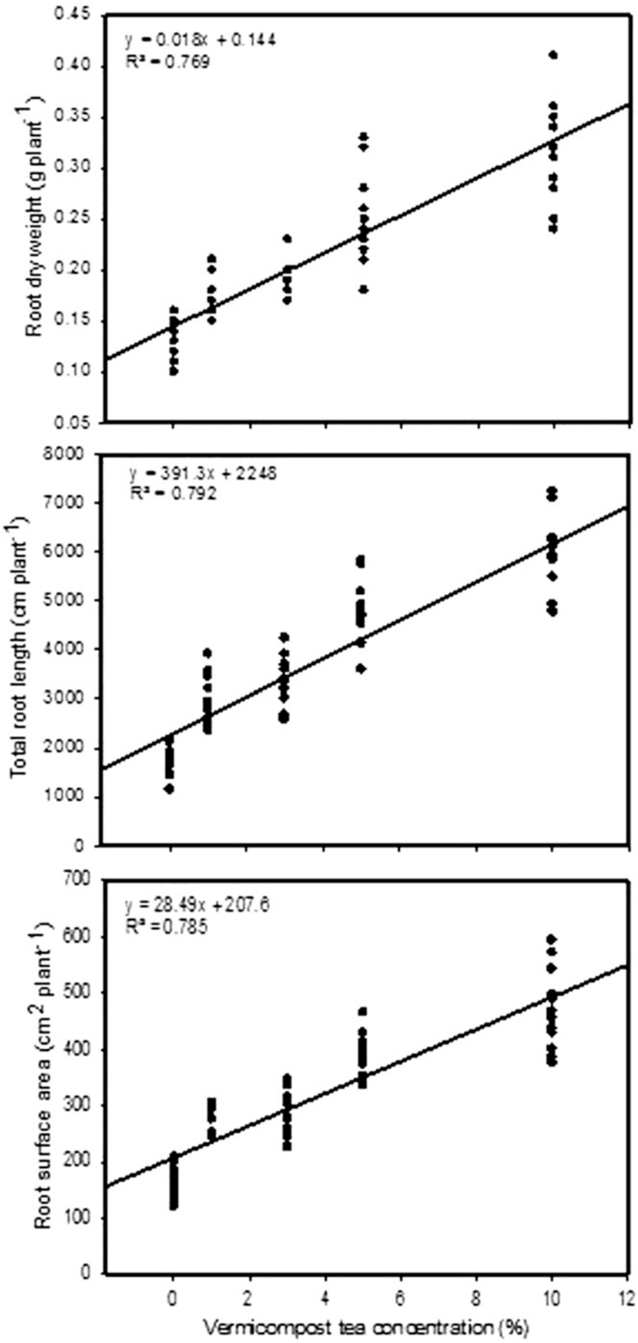

Fig. 2. Effect of vermicompost tea on root growth of pak choi in greenhouse trials (n = 60).

found, in which chicken manure resulted in the lowest aboveground dry weight, height, and tissue N content. No significant interactions between vermicompost tea type and fertilizer were found, indicating similar effects of compost teas in the three fertilizer treatments.

There was a significant interaction effect of vermicompost tea type and fertilizer type on the aboveground fresh weight (Fig. 4) and stem basal diameter (Table 3), indicating vermicompost tea effect varies with fertilizer type. Aboveground fresh weight was unaffected by vermicompost tea concentrations under soluble fertilizer treatment, resulting in non-significant linear ($P < 0.24$) and quadratic ($P < 0.84$) effects. Increasing concentration of vermicompost tea significantly increased aboveground fresh weight in the other two fertilizer treatments, resulting in significant linear ($P < 0.0001$) effect. Stem basal diameter was unaffected by vermicompost tea concentrations under Tankage treatment ($P < 0.1$), but increasing concentration of vermicompost tea significantly ($P < 0.0001$) increased stem basal diameter in the other two fertilizer treatments.

Effect on phytonutrients (Site B). Application of vermicompost teas significantly increased total carotenoids and total glucosinolates averaged across all fertilizer treatments (Table 3). The effect of vermicompost tea and fertilizer types on total phenolics was not significant and the overall mean was 4321 mg·kg^{-1} (dry weight basis). Increasing concentration of vermicompost tea significantly increased total glucosinolates across all fertilizer types, resulting in a strong ($\eta^2 = 0.49$) and significant linear effect. Quadratic effect was small ($\eta^2 = 0.05$) yet significant. Significant differences resulting from fertilizer type were found, in which the soluble fertilizer treatment resulted in the lowest total glucosinolates.

There was a significant interaction between vermicompost tea type and fertilizer type on total carotenoids. Increasing concentration of vermicompost teas significantly increased total carotenoids in chicken manure and soluble fertilizer treatments, resulting in significant linear effects. There was a strong ($\eta^2 = 0.46$) and significant ($P < 0.0001$) quadratic effect on total carotenoids under Tankage treatment, whereas the linear effect was small ($\eta^2 = 0.35$) but significant ($P < 0.01$). This suggests that total carotenoids increased at decreasing rate with increasing concentrations of vermicompost tea.

Effect on soil respiration and dehydrogenase activities (Site A). The effect of vermicompost tea and fertilizer types on soil respiration (μmol CO_2/fluxes/m^2/sec) was significant but the time was not significant (Table 4). The interaction of vermicompost tea and fertilizer types on soil respiration was not significant. Increasing concentration of vermicompost tea increased soil respiration across all fertilizer types, resulting in a significant linear effect. The effect of vermicompost tea, fertilizer types, and time on dehydrogenase activity in soil was significant, but their interaction was not significant. Dehydrogenase activity (μg·g^{-1} soil) in soil increased significantly with increasing concentrations of vermicompost tea after the third week of application across the fertilizer regimes (Fig. 5), resulting in a strong ($\eta^2 = 0.11$) and significant linear effects. Quadratic effect was small ($\eta^2 = 0.08$) but significant. Fertilizer effect was significant on soil respiration and dehydrogenase activities throughout the experiment period. Both soil respiration and dehydrogenase activities were significantly greater with application of chicken manure than that of Tankage and soluble fertilizer.

Discussion

Greenhouse experiment

All vermicompost teas, irrespective of concentration, significantly improved shoot and root growth of greenhouse grown pak choi. Increased overall root development with the application of vermicompost tea may have contributed to better nutrient uptake and increased leaf area. Greater leaf area of vermicompost tea-treated plants could have been linked with increased aboveground plant dry weight in this study as a result of greater light interception and photosynthesis (Aase, 1978; Williams, 1987). Increasing vermicompost tea concentration linearly and positively influenced the plant growth. This effect may, in part, be the result of higher concentration of

Table 1. Chemical properties of vermicompost and vermicompost tea (n = 3).

	pH, EC, dissolved oxygen concn and humic acid				
Vermicompost or tea	pH	EC ($mS\cdot cm^{-1}$)	DO ($mg\cdot L^{-1}$)	Humic acid ($mg\cdot g^{-1}$ or $mg\cdot L^{-1}$)	Moisture (%)
Vermicompost	6.9 (0.1)	3.2 (0.2)	NA	8.1 (0.3)	66.5 (0.1)
10% tea	7.7 (0.0)[z]	1.4 (0.0)	7.9 (0.0)	435.3 (10.6)	NA
5% tea	7.9 (0.1)	1.1 (0.0)	7.8 (0.0)	293.6 (4.5)	NA
Control	8.6 (0.0)	0.5 (0.0)	8.1 (0.0)	ND	NA

	Macronutrient concn						
Vermicompost or tea	Nitrogen	NO_3-N	NH_4-N	Phosphorus	Potassium	Calcium	Magnesium
	mg·g^{-1} or mg·L^{-1}						
Vermicompost	14.8 (0.3)	0.15 (0.02)	0.04 (0.01)	40.3 (0.8)	1.5 (0.1)	24.6 (0.2)	8.3 (0.1)
10% tea	131.0 (7.2)	130.4 (7.2)	0.1 (0.0)	17.3 (1.2)	40.1 (1.2)	73.9 (1.3)	84.7 (0.8)
5% tea	113.0 (2.1)	111.2 (2.9)	0.1 (0.0)	15.8 (0.3)	31.0 (0.7)	60.0 (0.5)	68.1 (0.6)
Control	0.8 (0.0)	0.6 (0.0)	0.0 (0.0)	0.1 (0.0)	3.0 (0.0)	10.7 (0.0)	14.5 (0.1)

	Micronutrient concn					
Vermicompost or tea	Sodium	Iron	Manganese	Zinc	Copper	Boron
	µg·g^{-1} or µg·L^{-1}					
Vermicompost	1100 (0.9)	6342.9 (15.9)	1431.5 (10.5)	696.8 (12.2)	115.80 (1.0)	27.0 (0.2)
10% tea	72.5 (1.1)	0.08 (0.0)	0.02 (0.0)	0.03 (0.0)	0.03 (0.0)	0.2 (0.0)
5% tea	69.4 (0.7)	0.03 (0.0)	0.01 (0.0)	0.02 (0.0)	0.02 (0.0)	0.2 (0.0)
Control	68.7 (0.1)	0.01 (0.0)	0.00 (0.0)	0.01 (0.0)	0.00 (0.0)	0.0 (0.0)

[z]Mean with SE in parenthesis.
EC = electrical conductivity; DO = dissolved oxygen; NA = not applicable; ND = not detected.
The units used for vermicompost and vermicompost tea are mg·g^{-1} or µg·g^{-1} and mg·L^{-1} or µg·L^{-1}, respectively.

Table 2. Effect of concentration of vermicompost tea on plant growth, tissue N, and phytonutrients in Site A (n = 12).

Fertilizer	Tea	Aboveground dry wt (g/plant)	Tissue N (g/plant)	Ht (cm)	Base diam (cm)	Total carotenoids (mg·kg^{-1} dw)	Total glucosinolates (mmol·kg^{-1} dw)
Tankage (Tkg)	10% tea	15.8 (0.6)[z]	0.77 (0.04)	25.6 (0.7)	7.6 (0.3)	1173 (12)	29.8 (1.1)
	5% tea	15.5 (0.4)	0.73 (0.02)	25.6 (0.7)	7.5 (0.2)	1223 (33)	27.0 (0.3)
	Control	12.3 (0.4)	0.61 (0.03)	22.9 (0.9)	7.5 (0.2)	861 (10)	24.1 (0.5)
Chicken manure	10% tea	13.7 (1.1)	0.49 (0.05)	23.8 (0.9)	7.9 (0.2)	1286 (79)	24.5 (0.6)
(Chix)	5% tea	11.4 (0.6)	0.42 (0.02)	22.3 (0.7)	7.6 (0.3)	1152 (30)	24.1 (0.6)
	Control	7.1 (0.5)	0.24 (0.02)	19.0 (0.7)	6.5 (0.2)	781 (20)	19.5 (0.6)
Soluble fertilizer	10% tea	16.3 (0.4)	0.74 (0.04)	25.0 (0.4)	7.9 (0.1)	1517 (196)	26.6 (0.8)
(Trip16)	5% tea	14.9 (0.7)	0.62 (0.03)	24.9 (0.7)	7.7 (0.1)	1214 (30)	22.1 (0.9)
	Control	12.0 (0.5)	0.37 (0.02)	21.5 (0.9)	7.1 (0.2)	745 (15)	17.2 (1.0)
Fertilizer (F)		****[y]	****	****	NS	NS	****
Chix vs. others		****	****	**	**	NS	NS
Tkg vs. Trip16		NS	***	NS	NS	NS	****
Compost tea (T)		****	****	****	****	****	****
Linear		****	****	****	****	****	****
Quadratic		*	*	*	NS	*	NS
F*T		NS	*	NS	*	NS	NS

[z]Mean with SE in parenthesis.
[y]NS, *, **, ***, **** = Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.
N = nitrogen; dw = dry weight.

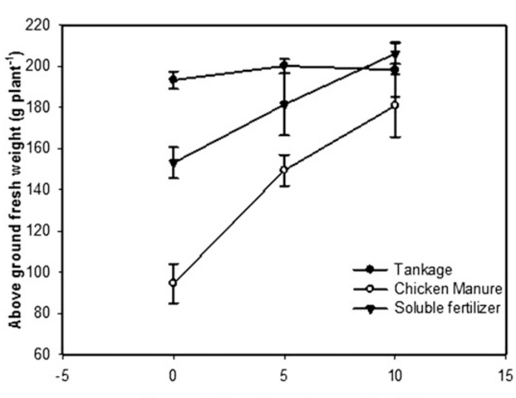

Fig. 3. Effect of concentration of vermicompost tea on aboveground fresh weight of pak choi under Tankage, chicken manure, and soluble fertilizer treatments in Site A. Plotted points are means of 12 samples, and error bars represent SE of the mean.

mineral nutrients and organic acids supplied by concentrated tea compared with dilute ones. Keeling et al. (2003) confirmed the higher growth-promoting effects of compost extract on wheat and oilseed rape with increasing concentrations. They observed significant positive effects with 33%, 17%, and 8% tea but did not see any response at greater dilutions than this. Hargreaves et al. (2008) and Reeve et al. (2010) also reported that the growth-promoting effect of compost extract was decreased by increasing dilutions of tea. The results of this greenhouse study are consistent with the findings of previous studies (Hargreaves et al., 2009; Keeling et al., 2003; Reeve et al., 2010).

Field experiment

The higher EC in 10% vermicompost tea relative to 5% tea is likely associated with

Table 3. Effect of concentration of vermicompost tea on plant growth, tissue N, and phytonutrients in Site B (n = 12).

Fertilizer	Tea	Aboveground dry wt (g/plant)	Tissue N (g/plant)	Ht (cm)	Base diam (cm)	Total carotenoids ($mg\cdot kg^{-1}$ dw)	Total glucosinolates ($mmol\cdot kg^{-1}$ dw)
Tankage	10% tea	26.6 (1.2)[z]	1.27 (0.06)	32.1 (0.4)	11.1 (0.2)	2444 (42)	16.8 (0.6)
(Tkg)	5% tea	24.4 (0.9)	1.17 (0.04)	31.6 (0.5)	10.9 (0.2)	2662 (93)	16.6 (0.6)
	Control	20.4 (1.1)	1.03 (0.05)	30.2 (0.5)	10.6 (0.1)	2004 (87)	13.1 (0.8)
Chicken manure	10% tea	24.3 (1.8)	1.17 (0.10)	31.5 (0.6)	11.1 (0.3)	2723 (111)	16.0 (0.8)
(Chix)	5% tea	23.3 (1.1)	1.03 (0.05)	30.3 (0.5)	10.4 (0.3)	2864 (157)	14.6 (0.8)
	Control	15.7 (1.2)	0.71 (0.06)	28.4 (0.7)	8.7 (0.3)	1923 (146)	11.1 (0.8)
Soluble fertilizer	10% tea	25.1 (0.3)	1.23 (0.02)	31.6 (0.5)	11.1 (0.3)	2794 (98)	14.5 (0.6)
(Trip16)	5% tea	24.0 (0.4)	1.25 (0.03)	31.6 (0.5)	10.8 (0.3)	2511 (52)	13.1 (0.6)
	Control	20.7 (0.6)	0.99 (0.03)	29.2 (0.6)	9.9 (0.2)	2172 (29)	9.6 (0.5)
Fertilizer (F)		**[y]	****	*	***	NS	****
Chix vs. others		**	****	*	****	NS	NS
Tkg vs. Trip16		NS	NS	NS	*	NS	**
Compost tea (T)		****	****	****	****	****	****
Linear		****	****	****	****	****	****
Quadratic		*	*	NS	NS	****	*
F*T		NS	NS	NS	**	*	NS

[z]Mean with SE in parenthesis.
[y]NS, *, **, ***, **** = Nonsignificant or significant at $P < 0.05$, 0.01, 0.00, or 0.0001, respectively.
N = nitrogen; dw = dry weight.

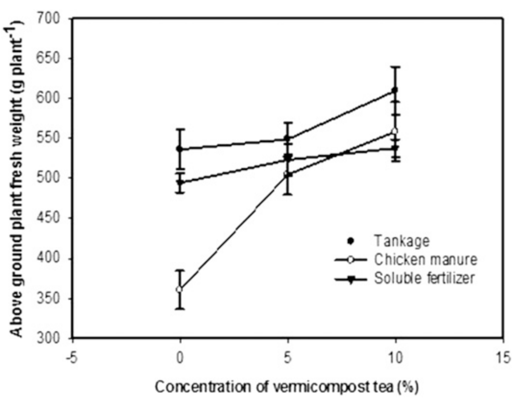

Fig. 4. Effect of concentration of vermicompost tea on aboveground fresh weight of pak choi under Tankage, chicken manure and soluble fertilizer treatments in Site B. Plotted points are means of 20 samples, and error bars represent SE of the mean.

higher levels of mineral nutrients and humic acid in 10% tea compared with 5% tea. Ten percent vermicompost tea contained ≈45% more humic acid, 15% more N, 30% more potassium as well as 20% more calcium and magnesium than that of 5% tea. The lower pH of 10% tea compared with 5% tea could have been linked with higher organic acids in concentrated tea compared with the more dilute one.

Application of vermicompost tea significantly enhanced aboveground plant dry weight, tissue N content, and plant height of pak choi grown in both the experimental sites across the fertilizer regimes. These results are consistent with findings of previous research (Gamaley et al., 2001; Hargreaves et al., 2009; Pant et al., 2009). Aboveground plant fresh weight of vermicompost tea-treated plants was significantly greater than that of control plants under chicken manure fertilization in both the sites, whereas aboveground plant fresh weight was unaffected by vermicompost tea application under Tankage treatment in Site A and under soluble fertilizer treatment in Site B. Slower release of available plant nutrients from chicken manure compared with Tankage and soluble fertilizer could be a possible explanation of a consistently greater plant growth response to vermicompost tea application over control under chicken manure fertilization than Tankage and soluble fertilizer. This supports the results of a previous study, which reported a strong relationship between N status of crop and yield across tea treatments (Pant et al., 2009).

Soluble mineral nutrients and microbial byproducts in vermicompost tea can enhance nutrient uptake from the soil and increase foliar uptake of nutrients. Arancon et al. (2007) reported that humic, fulvic, and other organic acids extracted or produced by microorganisms in vermicompost tea could induce plant growth by improving root development and nutrient uptake. Similarly, Pant et al. (2011) reported a greater root biomass, length, and surface area in pak choi plants treated with vermicompost tea compared with control. Nutrient analysis of vermicompost tea indicates that vermicompost tea supplied a considerable amount of soluble mineral nutrients and humic acid to the plant compared with the control.

Increased total carotenoid level in plant tissue in response to vermicompost tea treatments was associated with improved plant growth. This agrees with the findings of previous studies that reported higher carotenoids in plant tissue corresponded with increased plant growth at higher fertilizer rates (Hussein et al., 2006; Kopsell et al., 2007; Pant et al., 2009). Increased plant growth with the application of vermicompost tea may have contributed to greater synthesis of carotenoids across the fertilizer regimes in both trials.

Multiple studies have confirmed the positive relationship between N availability and total glucosinolates concentration of Brassica crops. Krumbein et al. (2002) reported that the levels of total glucosinolates were low with low N fertilizer in broccoli plants, whereas total glucosinolates levels were high at sufficient N supply. In another study, the levels of several glucosinolates decreased in leaves under N deficiency but accumulated in roots of *Arabidopsis thaliana* (Hirai et al., 2004). However, Chen et al. (2006) observed lower levels of total glucosinolates in pak choi at high levels of foliar N application. Applications of vermicompost tea contributed to increased N availability to plants, perhaps explaining the positive relationship between total glucosinolates and plant growth.

The absence of a vermicompost tea effect on total phenolics content of pak choi plants across the fertilizer regimes is likely the result of a general absence of nutrient stress. It has been previously demonstrated that N stress is associated with increased level of phenolics in plant tissue (Brown et al., 1984; Estiarte et al., 1994).

Soil respiration and dehydrogenase activity increased over time in the rhizosphere of vermicompost tea-treated plants. The increase in soil respiration may be explained by improved microbial decomposition of soil organic

Table 4. Effect of vermicompost tea on soil biological properties (n = 4).

Fertilizer	Tea	Soil respiration (CO_2 fluxes/µmol/m²/s)	Dehydrogenase activity (TPF µg·g⁻¹ soil)
Tankage	10% tea	6.9 (1.3)[z]	66.4 (3.7)
(Tkg)	5% tea	7.0 (0.8)	77.1 (5.3)
	Control	5.5 (0.5)	57.2 (4.9)
Chicken manure	10% tea	8.5 (0.9)	84.3 (6.9)
(Chix)	5% tea	9.6 (0.9)	85.13 (10.5)
	Control	6.0 (1.2)	69.3 (6.7)
Soluble fertilizer	10% tea	6.0 (0.7)	64.4 (3.8)
(Trip16)	5% tea	5.4 (0.9)	61.9 (1.7)
	Control	4.3 (0.8)	51.8 (5.3)
Fertilizer (F)		***[y]	***
Chix vs. others		****	****
Tkg vs. Trip16		*	*
Compost tea (T)		**	*
Linear		*	*
Quadratic		NS	*
Time (I)		NS	****
F*T		NS	NS
I*F		NS	NS
I*T		NS	NS
I*F*T		NS	NS

[z]Mean with SE in parenthesis.
[y]NS, *, **, ***, **** = Nonsignificant or significant at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.
TPF = 1,3,5-triphenyltetrazolium formazan.

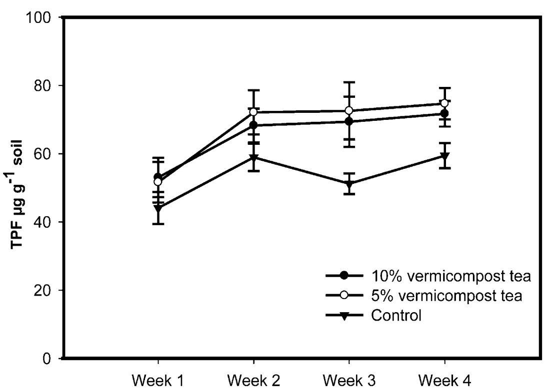

Fig. 5. Effect of vermicompost tea on dehydrogenase activity in soil (TPF µg·g⁻¹ of soil) across the fertilizer regimes over time. Plotted points are means of 12 samples, and error bars represent SE of the mean. TPF = 1,3,5-triphenyltetrazolium formazan.

matter. This effect might be the result of the greater availability of active organic carbon or enrichment of nutrients for the microbes through the addition of high organic carbon content of compost (Bernal et al., 1998; Sikora and Yakovchenko, 1996). Increased soil respiration and dehydrogenase activity in this study as a result of vermicompost tea applications implies a more efficient organic matter decomposition and mineralization in rhizosphere, which may have in turn contributed to better plant growth.

A higher ratio of vermicompost to water generally results in greater concentration of mineral nutrients, dissolved salts, and organic acids in the extract, which may either cause phytotoxicity or increase production costs. On the other hand, excessive dilution may reduce the effectiveness of vermicompost tea because very dilute concentrations may not contain sufficient amounts of nutrients or other compounds required for optimal plant growth. Increasing concentration of vermicompost tea (ranging from 1%–10% tea) linearly increased plant production, N uptake by plants, and phytonutrient contents along with improving soil biological properties in this study. These results agree with the findings of Akanbi et al. (2007) who reported that applications of 8% compost tea significantly increased plant growth of *Telfairia occidentalis* (fluted pumpkin) compared with that of 0% and 6% teas.

Conclusion

This study confirms previous reports of a positive influence of vermicompost tea on plant growth in greenhouse studies. More importantly, we document for the first time in the field an effect of vermicompost tea on important classes of secondary metabolites (carotenoids, phenolics, and glucosinolates). Within the range of concentrations evaluated (1%–10%), greatest plant growth response was observed with 5% and 10% vermicompost tea, indicating that the optimal water-to-vermicompost ratio for extraction is lower than 50:1 and is likely in the range of 10:1 to 20:1. The magnitude of plant response to vermicompost tea was greater for some traits under chicken manure fertilization compared with Tankage or synthetic mineral fertilizers. Our results suggest that this differential plant response to tea was largely a function of nutrient (N) availability, as demonstrated by a strong, linear correlation between plant growth and N uptake across fertilizer and compost tea treatments. Based on these results, increased nutrient uptake in tea treatments is hypothesized to be a result of: 1) nutrients added by teas; 2) improved nutrient mineralization as suggested by increased microbial activity in soil; and 3) the presence of humic acid in the tea.

Literature Cited

Aase, J.K. 1978. Relationship between leaf area and dry matter in winter wheat. Agron. J. 70: 563–565.

Akanbi, W.B., T.A. Adebayo, O.A. Togun, A.S. Adeyeye, and O.A. Olaniran. 2007. The use of compost extract as foliar spray nutrient source and botanical insecticide in Telfairia occidentalis. World J. Agr. Sci. 3:642–652.

Alef, K. 1995. Dehydrogenase activity. In: Alef, K. and P. Nannipieri (eds.). Methods in applied soil microbiology and biochemistry. Academic Press, London, U.K.

Arancon, N.Q., C.A. Edwards, R. Dick, and L. Dick. 2007. Vermicompost tea production and plant growth impacts. Biocycle 48:51–52.

Bernal, M.P., M.A. Sanchez-Monedero, C. Paredes, and A. Roig. 1998. Carbon mineralization from organic wastes at different composting stages during their incubation with soil. Agr. Ecosyst. Environ. 69:175–189.

Brown, P.H., Graham, R.B., and Nicholas, D.J.D., 1984. The effects of manganese and nitrate supply on the levels of phenolics and lignin in young wheat plants. Plant Soil 81:437–440.

Chen, X., Z. Zhu, X. Ni, and Q. Qiam. 2006. Effect of nitrogen and sulfur supply on glucosinolates in Brassica campestris ssp. chinensis. Agr. Sci. China 8:603–608.

Diver, S. 2001. Notes on compost teas: A 2001 supplement to the ATTRA publication "Compost teas for plant disease control." ATTRA publication, Fayetteville, Arkansas.

Estiarte, M., I. Filella, J. Serra, and J. Peñuelas. 1994. Effects of nutrient and water stress on leaf phenolic content of peppers and susceptibility to generalist herbivore Helicoverpa armigera (Hubner). Oecologia 99:387–391.

Gamaley, A.V., M.A. Nadporozhskaya, A.I. Popov, O.G. Chertov, N.V. Kovsh, and O.A. Gromova. 2001. Non-root nutrition with vermicompost extracts as the way of ecological optimization. Plant nutrition: Food security and sustainability of agro-ecosystems through basic and applied research. 14th International Plant Nutrition Colloquium, Hannover, Germany. Springer, The Netherlands. p. 862–863.

Gross, J. 1991. Carotenoids, p. 100–111. In: Reinhold, V.N. (ed.). Pigments in vegetables: Chlorophylls and carotenoids, New York, NY.

Hargreaves, J., M.S. Adl, P.R. Warman, and H.P.V. Rupasinghe. 2008. The effects of organic amendments on mineral element uptake and fruit quality of raspberries. Plant Soil 308:213–226.

Hargreaves, J.C., M.S. Adla, and P.R. Warman. 2009. Are compost teas an effective nutrient amendment in the cultivation of strawberries? Soil and plant tissue effects. J. Sci. Food Agr. 89:390–397.

Hirai, M.Y., M. Yano, D.B. Goodenowe, S.K., Kimura, T., Awazuhara, M. Arita, M. Fujiwara, and T. Saito. 2004. Integration of transcriptomics and metabolomics for understanding of global responses to nutritional stresses in Arabidopsis thaliana. p. 101.

Hussein, M.S., S.E. El-Sherbeny, M.Y. Khalil, N.Y. Naguib, and S.M. Aly. 2006. Growth characters and chemical constituents of Dracocephalum moldavica L. plants in relation to compost fertilizer and planting distance. Sci. Hort. 108:322–331.

Ingham, E.R. 2005. Compost tea: Promises and practicalities. The IPM Practitioner: The newsletter of integrated pest management. p. 1–5.

Kannangara, T., T. Forge, and B. Dang. 2006. Effects of aeration, molasses, kelp, compost type, and carrot juice on the growth of *Escherichia coli* in compost teas. Compost Sci. Util. 14:40–47.

Keeling, A.A., K.R. McCallum, and C.P. Beckwith. 2003. Mature green waste compost enhances growth and nitrogen uptake in wheat (Triticum aestivum L.) and oilseed rape (Brassica napus L.) through the action of water-extractable factors. Bioresour. Technol. 90:127–132.

Kopsell, D.A., T.C. Barickman, C.E. Sams, and J.S. McElroy. 2007. Influence of nitrogen and sulfur on biomass production and carotenoid and glucosinolate concentrations in watercress (Nasturtium officinale R. Br.). J. Agr. Food Chem. 55:10628–10634.

Krumbein, A., I. Schonhof, J. Ruhlmann, and S. Widell. 2002. Influence of sulphur and nitrogen supply on flavour and health-affecting compounds in Brassicaceae., p. 294–295. In: Horst, W.J., M.K. Schenk, A. Bürkert, N. Claassen, H. Flessa, W.B. Frommer, H. Goldbach, H.W. Olfs, V. Römheld, and B. Sattelmacher (eds.). Developments in plant and soil sciences, 92, Plant nutrition—Food security and sustainability of agro-ecosystems through basic and applied research. Kluwer Academic Publishers, The Netherlands.

Merrill, R. and J. McKeon. 2001. Apparatus design and experimental protocol for organic compost teas. Organic Farming Research Foundation. 4 Oct. 2010. <https://ofrf.org/publications/ib/ib09.pdf>.

Palmer, A.K., K.J. Evans, and D.A. Metcalf. 2010. Characters of aerated compost tea from immature compost that limit colonization of bean leaflets by Botrytis cinerea. J. Appl. Microbiol. 109:1619–1631.

Pant, A., T.J.K. Radovich, N.V. Hue, and N.Q. Arancon. 2011. Effects of vermicompost tea (aqueous extract) on pak-choi yield, quality, and on soil biological properties. Compost Sci. Util. 19:279–292.

Pant, A., T.J.K. Radovich, N.V. Hue, S.T. Talcott, and K.A. Krenek. 2009. Vermicompost extracts influence growth, mineral nutrients, phytonutrients and antioxidant activity in pak choi (Brassica rapa cv. Bonsai, Chinensis group) grown under vermicompost and chemical fertilizer. J. Sci. Food Agr. 89:2383–2392.

Radovich, T.J.K., M.D. Kleinhenz, J.G. Streeter, A.R. Miller, and J.C. Scheerens. 2005. Planting date affects total glucosinolate concentrations in six commercial cultivars of cabbage (Brassica olereacea L., Capitata group). HortScience 40:106–110.

Reeve, J.R., L. Carpenter-Boggs, J.P. Reganold, A.L. York, and W.F. Brinton. 2010. Influence of biodynamic preparations on compost development and resultant compost extracts on wheat seedling growth. Bioresour. Technol. 101:5658–5666.

SAS Institute Inc. 2003. SAS for Windows. SAS Institute Inc., Cary, NC.

Scheuerell, S.J. and W.F. Mahaffee. 2004. Compost tea as a container medium drench for suppressing seedling damping-off caused by *Pythium ultimum*. Phytopathology 94:1156–1163.

Sikora, L.J. and V. Yakovchenko. 1996. Soil organic matter mineralization after compost amendment. Soil Sci. Amer. J. 60:1401–1404.

Stern, J.L., A.E. Hagerman, P.D. Steinber, F.C. Winter, and J.A. Estes. 1996. A new assay for quantifying brown algal phlorotannins and comparisons to previous methods. J. Chem. Ecol. 22:1273–1294.

Valdrighi, M.M., A. Pera, M. Agnolucci, S. Frassinetti, D. Lunardi, and G. Vallini. 1996. Effects of compost-derived humic acids on vegetable biomass production and microbial growth within a plant (Cichorium intybus)-soil system: A comparative study. Agr. Ecosyst. Environ. 58: 133–144.

Welke, S.E. 2005. The effect of compost extract on the yield of strawberries and the severity of Botrytis cinerea. J. Sustain. Agr. 25:57–68.

Weltzien, H.C. 1990. The use of composted materials for leaf disease suppression in field crops. Monograph Brit. Crop Prot. Count. 45:115–120.

Williams, L.E. 1987. Growth of 'Thompson Seedless' grapevines. I. Leaf area development and dry weight distribution. J. Amer. Soc. Hort. Sci. 112:325–330.

Zaller, J.G. 2006. Foliar spraying of vermicompost extracts: Effects on fruit quality and indications of Late-Blight suppression of field-grown tomatoes. Biol. Agr. Hort. 24:165–180.