Compost and Compost Tea: Principles and Prospects as Substrates and Soil-Borne Disease Management Strategies in Soil-Less Vegetable Production

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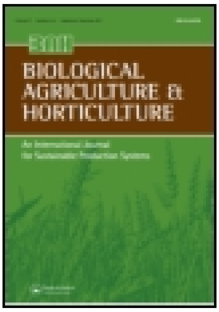

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Compost and compost tea: Principles and prospects as substrates and soil-borne disease management strategies in soil-less vegetable production

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Numerous studies have demonstrated the potential of composted organic wastes not only as substitutes for peat as a growth substrate but also to stimulate plant growth and suppress soil-borne diseases. The major impediment to the use of compost as substrates or biocontrol agents has been variation in physical and chemical characteristics and disease suppression levels across and within compost types, sources, and batches. Compost tea, a product of compost, has also been shown to suppress soil-borne diseases including damping-off and root rots (*Pythium ultimum*, *Rhizoctonia solani*, *Phytophthora* spp.) and wilts (*Fusarium oxysporum* and *Verticillium dahliae*). Although the mechanisms involved in disease suppression are not fully understood, sterilization of composts and compost teas has generally resulted in a loss in disease suppressiveness. This indicates that the mechanism of suppression is often, or predominantly, biological, although chemical and physical factors have also been implicated. The inoculation of composts with biological control agents, manipulation of compost tea production process, and the use of new techniques for organic matter characterization and microbial community profiling may improve the efficacy and reliability of disease control obtained.

Keywords: compost; compost tea; disease suppression; growing substrate; soil-borne disease

Introduction

The use of compost as a peat substitute, based on its disease suppressive properties, has been extensively reviewed by several authors (De Ceuster and Hoitink 1999; Hoitink and Boehm 1999; Hoitink and Fahy 1986; Hoitink et al. 2001; Ryckeboer 2001). However, most of these reviews do not adequately discuss issues such as the physical and chemical properties of compost as it relates to plant growth and performance. The inclusion of such issues in a review represents a more holistic view and lends to a greater understanding of the technical factors affecting the translation of findings into commercial vegetable production systems. Such an approach is useful in discussing the principles and prospectus of composts as substrates and biocontrol agents for soil-borne disease management in vegetable production. Even rarer is the inclusion of discussions on compost tea as a means of maximizing the potential of compost and as part of an arsenal of tools available to improve substrate health and to sustainably manage soil-borne diseases.

The demand for technical information on compost and compost tea made from readily available local waste materials has significantly increased over the last decade. This interest

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has come from both developed and developing countries as the practice and interest in commercial production of vegetables using soil-less media have increased amidst major long-term sustainability issues such as rising prices of imported peat-based growth media and other inputs (Jayasinghe et al. 2010), negative environmental and ecological impact of peat mining (Robertson 1993), and increasing generation of compostable waste material such as agro-waste, which is discarded to landfills (Acurio et al. 1998). At the same time, serious efforts are being made by most developing countries to address food and nutrition security through resource maximization and the development of rural communities through agriculture, appropriate technology, and entrepreneurship (Jagdeo 2007). Recycling biodegradable waste into compost and compost teas is being promoted as a viable option for treating waste material.

As well as the use of compost as a bulk fertilizer and soil ameliorant, there is considerable evidence that shows that compost and liquid preparations such as compost tea made from compost can suppress soil-borne diseases (Bonanomi et al. 2007; Lievens et al. 2001; Pane et al. 2011; Santos et al. 2011; Scheuerell and Mahaffee 2004; Spring et al. 1980). However, the effect of compost and compost teas on soil-borne diseases varies greatly depending on the properties of the compost as affected by compost formulation, the composting and compost tea brewing process, and the environmental conditions in which the material is used (Litterick and Wood 2009; Scheuerell and Mahaffee 2002).

The objectives of this review are to define composting, compost, and compost teas and extracts, to describe preparation methods, and to summarize the current knowledge of compost used as growth substrates in vegetable production. Current knowledge of the soil-borne disease suppression with compost and compost tea is also summarized as well as factors affecting the efficacy of these products. Mechanisms involved in the suppression of soil-borne diseases by compost and compost teas are also discussed and emerging areas of research are identified and briefly discussed.

Definition of composting, compost, compost extracts, and compost teas

Composting has been defined as a biological process through which microorganisms convert organic materials into useful end products, which may be used as soil conditioners and/or organic fertilizers (Buchanan and Gliessman 1991; Stoffella and Kahn 2001). The solid particulate products of composting, which are extracted during the maturation and curing phase are referred to as compost (Litterick and Wood 2009; Paulin and O'Malley 2008). Despite these definitions, the term composting and compost remain fairly ambiguous as compost has also been used to refer to end-products of other biological processes such as fermentation (Lee 1994; Lwin and Ranamukhaarachchi 2006) as well as to products extracted before the maturity and curing phase of the composting process. As such, more detailed and rigorous definitions as provided by Haug (1993) and Golueke (1982) will be used in this review to distinguish composting and compost from other biological processes and end products. Composting, is the controlled, microbial aerobic decomposition and stabilization of organic substrates, under conditions that allow the generation of high temperatures by thermophilic microbes, to obtain an end product that is stable, free of pathogens and viable weed seeds, and can be used in plant culture.

As with compost, the terms compost extract and compost tea have also been ambiguously defined. Both terms have been used interchangeably in studies to refer to liquid samples obtained from or through the use of compost by pressure, distillation, evaporation or treatment with a solvent (Cayne and Lechner 1989). However, for the purposes of this review, compost extracts and compost teas will be treated as different products. Compost extracts will be referred to as filtered products of compost mixed with any solvent, usually water, but not fermented or brewed (Scheuerell and Mahaffee 2002), and compost teas as filtered products of compost fermented in water (Litterick et al. 2004). Compost teas will be further distinguished into aerated and non-aerated compost teas with respect to the fermentation method used to prepare them. Aerated compost teas (ACT) will refer to products where the compost-water extract is actively aerated during the fermentation process (Litterick and Wood 2009). Non-aerated compost teas (NCT) will refer to products where the compost-water extract is not aerated, or receives minimal aeration only at the initial mixing stage of the fermentation process (Litterick and Wood 2009).

Compost and compost tea production

Compost production

Traditionally, compost has been produced in rural farming areas of most developing tropical countries using small-scale, slow-rate, open composting methods, particularly heap and pit structures (Persad 2000), whereas in urban areas and most developed countries, larger scale techniques involving windrow or in-vessel have been adopted. Characteristic of heap and pit methods are long composting times, inconsistent compost quality, poor ergonomic qualities, and a relatively high demand for labour and space (Persad 2000). In the context of increasing rates of organic waste generation in both rural and urban areas, windrow and in-vessel systems, with higher turnovers, which can produce end products of a more consistent quality, have been used (Diaz et al. 2007).

Windrow systems are characterized by the accumulation of substrates into piles, typically 1.5 to 2.5 m high, formed into long rows called windrows. Typically, windrow systems are further subdivided into turned and forced air or static pile windrows on the basis of aeration (Diaz et al. 2007). In turned windrow systems, aeration is achieved by periodically turning the pile either manually or by mechanical means. In contrast to forced-air or static pile systems, the compost mass is disturbed to achieve aeration and air is not forced upward through the composting mass or pulled downward and through the pile (Diaz et al. 2007).

Open turned windrow systems are generally considered low-cost and suitable for composting low-hazard materials including green or garden waste (Litterick and Wood 2009), whereas the major interest in aerated static pile systems is in its apparent utility in composting sewage sludge and capacity to deodorize effluent air streams (Diaz et al. 2007). Turned windrow systems have been criticized for their potential threat to public health, particularly when the process involves human excrement and residues from animals that harbour disease organisms pathogenic to man (zoonoses) (Diaz et al. 2007). The main features of turned windrow composting systems that relate to the critique are that temperatures that are lethal to the pathogen do not generally prevail throughout a windrow and the turning procedure may play an important role in recontaminating the sterilized material with non-sterilized materials from the outer layer of the windrow (Diaz et al. 2007). Other limitations of turned windrows are the potential for objectionable odours due to improper and insufficient turning and a relatively slow rate of degradation with a greater space requirement (Diaz et al. 2007).

With in-vessel systems, all or part of composting takes place in a reactor and the process tends to be more controlled or suited for quick primary stabilization of the composting mass. In-vessel systems are generally thought to be more suitable for composting food wastes and wastes containing animal by-products (Litterick and Wood 2009). The process normally lasts from 1 to 15 days but is highly dependent on substrate properties (Diaz et al. 2007). Materials exiting the reactors at the end of this rapid degradation phase are usually placed in windrows for curing and maturation (Dziejowski and Kazanowska 2002). In-vessel systems are generally subdivided into vertical, horizontal, and diagonal or rotating drum systems on the basis of the position of the reactor or classified as a function of the material movement into static and dynamic systems. Unlike the static system, the compost mass is continuously mixed in in-vessel dynamic systems. The sophistication and cost of these composting systems both within and across the major groups identified vary greatly, depending on the nature of the material being composted and on the end use of the compost being prepared (Litterick and Wood 2009). Post-processing, which is done to refine the finished compost to meet regulatory and market requirements, can involve a number of other processes including screening and size reduction, which may significantly increase costs and labour requirements (Diaz et al. 2007). Generally, the economics of windrow systems are more favourable than some mechanized systems, particularly in countries where there is excess labour.

Notwithstanding the composting system used, the three phases that occur during the composting process and depict temperature as a function of composting time can be observed. These phases include (1) the mesophilic phase, a rise in compost temperatures above ambient temperature to approximately 40°C; (2) the thermophilic phase, compost temperature > 40°C; and (3) the cooling and maturation phase, a decrease in compost temperature to eventual range of ± 3°C of ambient temperature (Epstein 1997). For the composting process to be optimal, ideally the input materials must be sufficiently moist (40–60%), have a sufficiently open structure to allow air to penetrate the mass, and must have a suitable carbon to nitrogen (C:N) ratio of about 25:1 to 40:1 (Litterick and Wood 2009). Rarely is only one feedstock composted because the C:N ratio of most materials does not fall within the suitable range. For example, sawdust typically has a C:N ratio of 60:1 and vegetable waste, a C:N ratio of 12:1. Therefore, these feedstocks must be mixed with other materials such as manure and mineral fertilizers to achieve the suitable C:N ratio.

Compost tea production

Most compost tea reported here was made using predominantly two approaches, aerated and non-aerated methods. Both methods involve fermenting well-characterized compost in water for a specific time period and require the use of a fermentation or brewing vessel, inoculum (compost), water, incubation and filtration prior to application (Litterick and Wood 2009; Scheuerell and Mahaffee 2002). Nutrients may be added before or after brewing and additives or adjuvants may be added prior to application.

There has been continuous debate regarding the benefits of aeration during the compost tea production process (Brinton et al. 1996; Ingham and Alms 2003). As such, studies on the efficacy of aerated and non-aerated compost teas with respect to compost source and age, optimum brewing time, benefits of aeration, addition of nutrients, phytotoxicity, cost, energy input, and mechanism of disease suppression are numerous (Ingham and Alms 2003; Litterick and Wood 2009).

The majority of scientific literature supports the suppression of phytopathogens and plant diseases by non-aerated compost teas (NCT) (Cronin et al. 1996; Ketterer and Schwager 1992; Tränkner 1992,), which has been associated with low-cost and low-energy input (Weltzien 1991). However, NCT have been suggested to cause phytotoxicity and provide the optimal environment for human pathogen regrowth (Litterick and Wood 2009; Scheuerell and Mahaffee 2002). Contrastingly, aerated compost teas (ACT) have been associated with shorter brewing time (Scheuerell and Mahaffee 2002), higher microbial mass and diversity (Ingham and Alms 2003), lower or no phytotoxicity (Ingham and Alms 2003), and less than ideal environment for the proliferation of human pathogen (Ingham and Alms 2003). Contrary to claims concerning the suitability of environment of NCT for the proliferation of human pathogens, Ingram and Millner (2007) reported that potential for regrowth of human pathogens *Escherichia coli* O157:H7, *Salmonella*, and faecal coliforms was not compost tea brewing method specific but was greatly dependent on the addition of nutrient supplements at the beginning of the brewing process. In fact, they reported that ACT sustained higher concentrations of *E. coli* O157:H7, *Salmonella*, and faecal coliforms than did NCT when nutrient supplements were added. Scheuerell and Mahaffee (2002) and Litterick and Wood (2009) both reported that there is little evidence to substantiate the claims that NCT can cause phytotoxicity. There are a growing number of companies designing and selling apparatus to produce ACT. However, to date, the common designs of apparatus used to produce ACT include showering recirculated water through a porous bag of compost that is suspended over an open tank (Merrill and McKeon 2001), recirculating water through a vortex nozzle mounted above a tank (Ingham and Alms 1999), injecting air through a hollow propeller shaft (SoilSoup 2012), venturi nozzles (Sustainable Agricultural Technologies, Inc. 2012), aquarium stones (Ingham 2000), or fine bubble diffusion mats (Growing Solutions Incorporated 2012).

Generally, NCT are produced by mixing one volume of compost with 4 to 10 volumes of water in an open container. Initially, the mixture is stirred, then allowed to stand undisturbed at 15–20°C for at least three days (Weltzien 1991) with no or minimal stirring. To facilitate the release of microbes from the compost particles, Brinton et al. (1996) suggested stirring NCT every two to three days. To avoid a sampling error when considering experimental designs for *in vitro* inhibition screening with NCT, Yohalem et al. (1996) recommend that at least 500 g of compost be used in the brewing process. Container size used to produce NCT varies from small buckets to units that can hold several thousand litres. Notwithstanding the methods and technologies used to produce compost and compost tea, our understanding of, and research into, compost and compost tea, particularly in some developing countries, is at the infancy stage. Studies aimed at investigating and modelling response patterns of key physico-chemical parameters during composting and compost tea production process are needed. Such studies are needed to develop effective monitoring, troubleshooting, and decision-making systems that can be used to optimize composting and compost tea production under a wide variety of environmental conditions as well as assist in end-product attribute development. One such product which can be developed and will have a great impact on the sustainability of vegetable production using soil-less media is a peat alternative growth substrate.

Composts as seedling starter and transplant growth substrates

Unlike plants grown in the field, the root systems of containerized plants are restricted to small volumes of growth substrates which act as a reservoir for nutrients and water and provide oxygen for root respiration and support for the plants throughout the crop production cycle (Kuo et al. 2004). This presents unique production and management challenges that are not normally faced in open-field cultivation of vegetable crops. In an attempt to address these challenges, research on peat and peat alternative growth substrate, including those involving the use of composts made from various feedstocks, has been conducted over many years (Table 1). Most of these studies involving composts have focused on the development of containerized growth substrates for ornamental plants (Fitzpatrick 2001). Fewer studies have assessed the immediate and post-immediate effect

Table 1. Summary of container experiments examining the use of composted waste materials as alternative substrates to peat-based media or soil.

Compost	Rate (%)	Crop response	Factors affecting response	Reference
Newspaper/horse manure (NHMC)	100 (v/v)	Biomass (shoots, roots, and leaves) and nutrient concentration in leaf of tomato in NHMC = those in peat-based substrate or coconut fibre (control)	Good chemical and biological properties of NHMC	Ball et al. 2000
Green waste (GWC)	30 (v/v)	Tomato plant dry weight in GWC (30%) + composted pine (50%) + pumice (20%) = conventional bark-pumice mixes	Change in physical properties and nutrient availability	Spiers and Fietje 2000
Tobacco residue, yard leaf (YL), sewage sludge (SS) + rice hull, SS + YL and raw diary manure (RDM)	15, 30, 45 (v/v)	All potting mixtures produced significantly higher tomato biomass than the control (soil + sand) and RDM	Correct balance between the compost nutrient supply and the porosity and aeration	Hashemimajd et al. 2004
Sweet sorghum bagasse + pine bark	33, 67, 100 (v/v)	Tomato seed germination in compost (>67%) < peat based substrate	High salt concentration	Sánchez-Monedero et al. 2004
Brewery sludge		Tomato, broccoli and onion transplant growth and nutritional status not negatively affected by compost treatments	Salt tolerance level as it relates to plant growth was not breached	
Food residuals /yard waste (FR)	50, 100 (v/v)	Except for HB or media containing HB % germination of lettuce and tatsoi = peat based substrate (PBS).	Higher nitrogen availability in FR	Clark and Cavigelli 2005
Straw horse bedding (HB)		Plant height and marketable of both crops in FR (100%) = PBS Plant growth in all other treatments < PBS	High salinity, inhibition of nitrogen mineralization	
On farm compost	10, 20, 30, 40, 50 (v/v)	Height, leaf area, shoot, dry weight, and root dry weight of bell pepper in compost treatments > Pro-mix at 51 days after seeding	Growth enhancement was partly due to the mineral nutrients contained in the compost	Diaz-Perez et al. 2006
Sewage sludge (SS)	15, 30, 50 (v/v)	Broccoli germination = peat (P) substrate at all SS substitution rate. Yield in SS (30%) > P Macro and micronutrients in SS (50%) > P	Nutrient and water uptake	Perez-Murcia et al. 2006

Green waste-derived compost (GWC)	50, 80 (v/v)	Lettuce biomass production and leaf chlorophyll content in GWC (80%) > control (100% vermicompost)	Pure worm cast inhibited plant growth and depressed N content	Ali et al. 2007
Forestry wastes/ solid phase of pig slurry (3:1 by volume)	50, 75, 100 (v/v)	Tomato root dry weight, no. of leaves > in peat-based substrate	A higher nutrient availability, particularly nitrogen and advance on seedling emergence	Ribeiro et al. 2007
Livestock manure (LMC)	100 (v/v)	Yield and nutrient uptake of cucumber in LMC = to that in peat-based substrate	Physical and chemical properties of the compost	Schroeder and Sell 2007
Grape marc and cattle manure, grape marc and poultry manure	25, 50, 75 (v/v)	No yield and nutritional status loss of lettuce, chard, broccoli, and coriander treated with composts (25–50%) compared with peat	Adequate physical, physico-chemical, and chemical properties	Bustamante et al. 2008
Municipal solid waste (MSWC)	30, 65 (v/v)	Quality indices of tomato seedlings in white peat (65%) + MSWC (30%) = conventional mixtures of old and white peat sphagnum (control)	Correct balance between the compost nutrient supply and the porosity and aeration provided by white peat	Herrera et al. 2008
Green backyard compost		Lower tomato and lettuce germination percentage in undiluted mixes < diluted mixes or loam soil (control).	High EC in undiluted mixes	Alexander 2009
		Tomato heights and biomass in the undiluted mixes > diluted mixes but = to control	Nutrient availability	
Winery-distillery (WD) + citrus juice waste (WDC1)	20, 40, 60 (v/v)	Germination of lettuce in WDC2 = peat moss (PM).	Salinity did not affect germination	Bustamante et al. 2009
WD + tomato soup waste (WDC2)		Germination of lettuce in WDC1 and WDC3 < PM.	High salinity	
WD + cattle manure (WDC3)		Germination of watermelon in WDCs (60%) < in PM.	Nutrient availability	
		Lettuce and watermelon in WDC2 (20–40%) best transplant morphological and nutritional aspects		
Urban solid wastes, sewage treatment plant, and vegetable wastes		Increasing doses of compost substitution decreased germination speed of watermelon and tomato.	High EC affected germination speed	Díaz-Pérez et al. 2009

(*Continued*)

Table 1 – *continued*

Compost	Rate (%)	Crop response	Factors affecting response	Reference
		High compost doses increased the number of leaves and stem diameter and reduced the stem length and the stem diameter/stem length ratio	Higher nutrient availability	
Garden wastes and cow manure	0, 10, 20, 40, 60, 100% (v/v)	Quality of tomato and cucumber transplant from 100% compost = peat (100%)	Nutrient availability and pH and EC level were not excessively high	Ghanbari Jahromi and Aboutalebi 2009
Cow manure	10, 20, 50, 75, 100 (w/w)	At 10% and 20% inclusion rate, tomato aerial and root biomass, no. of leaves, leaf area, root volume > in peat based substrate.	Changes in the physical properties of the substrates due to inclusion of compost at low doses.¯	Lazcano et al. 2009
		Inclusion rate of ≥ 50% caused mortality	Plant mortality due to excessively high pH, EC and Cl	
Spent mushroom substrate (SMS)	25, 50, 75, 100 (v/v)	Tomato, courgette, and pepper seed germination of SMS (25–75%) = peat (P). Tomato growth in SMS (25–100%) = P	Tolerance of tomato to salinity	Medina et al. 2009
Yard leaf manure (YLM)	1, 3, 6, 9 (w/w)	Corn dry matter content of all YLM treatments < soil only. However, concentrations of N, P, K, Ca, and Mg corn plant for all YLM treatments > soil only	Low levels of available nitrogen in compost	Kalantari et al. 2010
Sewage sludge sugarcane (SSC)	40, 60 (v/v)	Growth and nutrition of lettuce in SSC-synthetic aggregate mixes > than those in peat based substrate (control)	Adequate physical and chemical properties compared to peat	Jayasinghe et al. 2010
Sewage sludge	15, 30, 45 (v/v)	Pepper leaf, shoot, and root dry matter, fruit yield and no. of fruits/plant > peat based mix (control)	Nutrient availability (particularly N) higher in compost	Pascual et al. 2010
Coffee pulp (CP)	10, 50 (v/v)	At CP (10%) tomato serial biomass, seedling height, and no. of nodes/plant > pro-mix	Improvement in physico-chemical and biological properties with the inclusion of CP	Berecha et al. 2011

Spent mushroom compost (SMC)	15, 25, 35, and 45 (v/v)	Cucumber fruit number and plant height in SMC (15% and 25%) > sandy-loam soil medium (control)	Soluble salts leached out, nutrient availability	Gonani et al. 2011
Olive pomace waste (OPC)	20, 45, 70, 90 (v/v)	Tomato seedling performance (fresh and dry biomass, stem length), in GWC (20%, 45%) and OPC 20% > peat based substrate (control)	Physical properties and EC as well as nutrient availability	Ceglie et al. 2011
Green waste (GWC)				
Palm waste (PW)	50 (v/v)	Cucumber growth and yield generally highest in PW + perlite (50/50%)	Improvement in the physical and chemical properties of mixes	Pooyeh et al. 2012

of composts as growth substrates or components of growth substrate on the performance of vegetable crops at the seedling and post seedling stage (Sánchez-Monedero et al. 2004; Walker et al. 2006).

Reports concerning the evaluation of composts as seedling starter substrates for the production of vegetable crops include work done primarily on solanaceous and cruciferous crops, corn, cucurbits, and legumes (Roe 2000). For example, Roe and Kostewicz (1992) reported that there was no significant difference between germination percentages of tomato and watermelon sown in yard trimming-grass clipping compost (100% v/v) and in a peat-lite control treament. Similar results were obtained by Ribeiro et al. (2007), who found that germination rate and growth of tomato seedlings increased with increasing doses of forest waste-pig slurry compost substitutions. They reported that tomato seedling growth was highest when peat was totally replaced by compost (100% v/v).

In contrast, Lazcano et al. (2009) found that substituting peat with low doses of cow manure compost (10% and 20% w/w) and high doses of vermicompost (75% and 100% w/w) produced significant increases in aerial and root biomass of tomato plants in comparison with peat (100% w/w). Lazcano et al. (2009) also reported that these treatments significantly improved plant morphology, resulting in a higher number of leaves and leaf area and increased root volume and branching. They concluded that total replacement of peat by vermicompost was possible while doses of compost higher than 50% (w/w) caused prompt plant mortality.

Unlike Lazcano et al. (2009), substitution doses of composts reported by Ribeiro et al. (2007) were not limited by high electrical conductivity (EC) values (≥ 3.7 dS m^{-1}), which may partly explain the differences in the results. Both research teams attributed the enhanced growth to enhanced bulk density of the growing media and to the decrease on total porosity and amount of readily available water in the container. Additionally, Lazcano et al. (2009) cited the nutrient-rich and biologically active properties of the compost and vermicompost as the cause for improved plant morphology.

Other researchers have recommended various compost substitution ratios based on germination rate and indices, seedling and crop performance results, and use limitations of composts due to their physical, chemical, and biological properties (Bustamante et al. 2008; Ostos et al. 2008; Spiers and Fietje 2000). It is worth noting that due to the greater sensitivity of seeds and seedlings to phytotoxic compounds, the quality standards for compost to be used as seedling starter substrate are generally more stringent than those to be used for transplant substrates or potting mixes (Kuo et al. 2004). To this end, there are some types of composted wastes which have shown to be acceptable replacements and substitutions for sphagnum peat in transplant substrate or potting media. For example, newspaper/horse manure-based compost was found to be a good alternative to peat-based compost for the post-seedling cultivation of tomato plants (Ball et al. 2000). In their study, Ball et al. (2000) noted that no phytotoxic compounds were detected in the newspaper/horse manure-based compost, and differences in shoots, roots, or leaf biomass or in the nutrient concentrations of leaf material among the compost treatment and the controls (peat-based compost and coconut fibre) were not significant.

In contrast to Ball et al. (2000), Stoffella and Graetz (1996) found that tomato transplanted in pots with compost or compost mixtures had higher shoot weights, thicker stems, and larger shoot to root ratios than plants grown in unamended field soil. Stoffella and Graetz (1996) used a compost made from filter cake, a sugarcane (*Saccharum officinarum*) processing waste, and tomato that were transplanted into pots filled with a 1:1 (v/v) mixture of the compost and a sandy field soil, the field soil only, or the compost only. In a more recent study, Diaz-Perez and Camacho-Ferre (2010) concluded that blond peat in transplant substrates could be partially substituted at a rate of 25–50% v/v by composts to grow tomato seedlings cv. Dakapo, providing that the EC was $< 2.5\,dS\ m^{-1}$. The compost used in the study was produced from solid urban waste, vegetable waste, and vine pomace.

Notwithstanding, the difficulty that exists in comparing the results of various studies owing to the wide variation in experimental conditions and factors as well as cultural practices including fertilizer application rates, production cycle, length of the experiments, it is clear that the amount of compost component in a growing substrate depends on type and quality of the compost, plant species to be grown, and growers' production system. Therefore, there is no one standard seedling starter or transplant substrate that can be recommended for all crops produced under all growing conditions.

In most of the aforementioned peat alternative containerized growth substrate studies, the resulting positive growth, yield, and improved nutritive value response of the vegetable crops has been attributed to the improved physical structure of the containerized media, increases in populations of beneficial microorganisms, and the potential availability of plant growth influencing substances produced by microorganisms in the composts or vermicomposts. In short, these resultant attributes have been cited as the advantages that compost has over peat as a growth substrate or component of growth substrate (Kuo et al. 2004).

It also is clear that most of the work on the use of composts as growth substrates has been conducted under temperate environmental conditions using waste streams that either differ from those in the tropical regions or are not available in sufficient quantities for local exploitation. This, along with the lack of detailed studies on change in the physical, chemical, and biological characteristics of compost and its effect in and across crop production cycles, has remained a relatively poorly researched area and a constraint to the adoption of compost as an alternative to peat by greenhouse farmers (Kuo et al. 2004).

Quality of compost and its effect on plant response

Though varied, the criteria used to evaluate compost quality in relation to its use as soil-less growth substrate or component of soil-less growth substrate have normally consisted of an assessment of physical (water holding capacity, bulk density, total pore space), chemical (cation exchange capacity, electrical conductivity, buffer capacity, pH, heavy metals and potentially toxic elements), and biological (absence of pathogens, maturity and plant growth performance) characteristics (Brinton 2000). Specific quality recommendations and guidelines have been made for the use of composts as soil-less growth substrates or components of soil-less growth substrates (Abad et al. 1993; Zapata et al. 2005).

Yeager et al. (2007) recommended that nursery production media should possess the following physical and chemical characteristics after irrigation and drainage (% volume basis): a total porosity of 50% to 80%, air space of 10% to 30%, water holding capacity of 45% to 65%, a bulk density of 0.19 to $0.70\,g\ cm^{-3}$, a pH between 5.0 to 6.0, and an EC between 0.2 and $0.5\,dS\ m^{-1}$. Recommended physical and chemical characteristics for containerized substrates were either similar to, or differed considerable from, those of nursery media, particularly with reference to some parameters. For example, Maronek et al. (1985) recommended that air space of containerized substrate should range between 15% and 40% and container capacity should range from 20% to 60%, bulk density between 0.3 and $0.8\,g\ cm^{-3}$, pH between 4.5 and 6.5, and EC from 0.6 to $1.5\,dS\ m^{-1}$.

The end use primary test values recommended for compost to be used as growth substrates also varied across countries and certifying agents (Table 2). Notwithstanding these variations in standards, research and field experience have shown that the typical factors limiting the inclusion rate of compost are pH, which affects seed germination, root growth, and nutrient availability (Hornick et al. 1984); high soluble salt concentration, which also affects seed germination and plant growth as well as water and nutrient uptake (Ribeiro et al. 2007; Vavrina 1994); maturity as unstable and immature compost may contain phytotoxic compounds, which affect seed germination capacity and rate, plant growth, and nutrient availability (Hadar et al. 1985); and water-holding capacity (WHC) and particle size, which directly affect plant growth due to their relation to aeration and water and nutrient availability (Sterrett and Chaney 1982; Vavrina et al. 1996).

Factors affecting compost quality

Feedstock type, compost formulation, and composting process, and system and management have all been reported to affect compost quality and use (Haug 1993; Rynk 1992; Sullivan and Miller 2000). For instance, Sullivan and Miller (2000) noted that final pH of compost is highly dependent on the chemical composition of feedstock, as waste material such as wood may be quite acidic, while others, for example, lime-treated bio-solids, may be a significant source of alkalinity. Similar dependencies have been reported between feedstock characteristics and soluble salts concentration, nature of microbial populations, presence of phytotoxic compounds, and matrix physical properties of the end product compost. For example, compost containing composted leaves and woody materials (Spiers and Fietje 2000), municipal solid waste co-composted with bio-solids (Vavrina 1994), spent mushroom compost (Lohr et al. 1984), and municipal leaf (Sawhney 1976) and cow manure (Bardhan et al. 2009) have frequently been cited as having high soluble salts concentrations. Reports also showed that compost prepared from tree barks and other lignocellulosic substances tends to become colonized mainly by *Trichoderma* spp. (Kuter et al. 1983); biosolids, municipal solid waste (MSW), and sewage sludge tend to contain heavy metals and toxic organic pollutants (Chaney and Ryan 1993; Kuo et al. 2004; Paulsrud et al. 2000), and slurry gives poor physical characteristics and aeration (Brito et al. 2008).

Factors depending on the formulation of composting mix such as nutrient balance, pH, particle size, porosity, and moisture, as well as process management factors including O_2 concentration, temperature, and water content, all affect the composting process and, by extension, compost quality (Bernal et al. 2008). Bernal et al. (2008) reported that nutrient balance outside the adequate C:N ratio range of 25–35 affects the rate of the compost

Table 2. End-use test values recommended for compost: Category potting mixes[a].

Test parameter	German	Austrian	WERL (USA)
Salt	<2.5 g l^{-1}	<2.5 g l^{-1}	<2.5 mmhos cm^{-1}
Avail-N	<300 mg l^{-1}	<800 mg l^{-1}	100–300 mg l^{-1}
Phosphate	<1200 mg l^{-1}	<800 mg l^{-1}	800–2500 mg l^{-1}
Potassium	<2000 mg l^{-1}	<1500 mg l^{-1}	500–2000 mg l^{-1}
Maturity	Dewar V	Pass plant test	Solvita 7-8
Organic matter	$>15\%$	$>20\%$	$>30\%$
pH	declared	5.5–7.0	6.0–7.0
Foreign	max 0.5% $>$ 2 mm	max 0.5% $>$ 2 mm	$<1\% >$ 2 mm

Note: [a] Assuming 40–50% of mix (v/v) is compost.
Sources: Fröhlich et al. (1993); Weimer and Kern (1989, 1992); Brinton (2000).

process as well as the concentration of nutrients, particularly inorganic nitrogen, available in the end product. They also noted that proper aeration, that is, an oxygen concentration between 15% and 20% (Miller 1992), controls the temperature, removes excess moisture and CO_2, and provides O_2 for biological processes. Factors such as O_2, compost temperature, and rate of decomposition can be controlled by the use of in-vessel or automated composting systems which generally produce compost of a more consistent quality, which is particularly important where compost is used as a disease suppressive substrate.

Composts as substrates to suppress damping-off and root rot diseases

Numerous container-based studies have consistently demonstrated suppressive effects of composts against soil-borne diseases such as damping-off and root rots (*Pythium ultimum, Rhizoctonia solani, Phytophthora* spp.) and wilts (*Fusarium oxysporum* and *Verticillium dahliae*) (Table 3). In an early pioneer study, Spring et al.(1980) found that the percentage kill of three-week-old apple seedlings was significantly lower in bark compost container medium than in a peat medium after inoculation with varying concentrations of *P. cactorum* zoospores and oospores. Similar results have been reported in more recent work by authors using various compost types, including grass clippings (Boulter et al. 2000; Nakasaki et al. 1998) and MSW (Pascual et al. 2002), for a range of crops and production systems. In some cases, it was reported that the levels of disease control by the composts were either equal to or greater than the level of control achieved using commercial fungicides (Ownley and Benson 1991).

However, the level of disease control differed significantly, both between and within studies, and there was no clear trend in the level of control of the same pathogen obtained in different crop species. Variation in the compost inclusion rates, control media (soil, sand, and peat), organic waste used, and the degree of decomposition of the compost, may partly explain these differences. Though most container-based studies were conducted with artificially introduced pathogen propagules, it is difficult to determine which compost amendments are most effective in controlling particular pathogens due to the wide variation in experimental conditions among studies.

Notwithstanding these issues, some of the research work has resulted in the development of useful commercial products. The most notable commercial application has been the use of composted bark in the United States container-produced ornamentals sector to suppress several soil-borne plant pathogens including *Phytophthora, Pythium* and *Rhizoctonia* spp. (Nelson et al. 1983; Spring et al. 1980). Despite the success of research and commercial ventures such as composted bark substrates, much is still not known about factors affecting suppressivity of compost and mechanisms by which plant diseases are controlled.

Factors affecting disease suppression induced by compost

Several authors have reported that feedstock type and composting system, organic matter decomposition level and compost maturity, physical, chemical, and biological attributes of compost, and inoculation of compost with biological control agents, all affect the disease suppressive ability of the compost (De Clercq et al. 2004; Hoitink et al. 1996; Litterick and Wood 2009). In a study using peat potting media amended with composts, Pane et al. (2011) found that compost derived from animal manure showed the largest and most consistent suppression of *P. ultimum, R. solani* and *Sclerotinia minor.* In contrast, Erhart

Table 3. Summary of container experiments examining the use of compost to suppress soil-borne diseases in vegetable crops.

Compost materials	Phytopathogens	Crop plant	Summarised effects	References
Hardwood bark (HBC)	*Pythium ultimum*	Tomato	HBC substituted at 66% (v/v) for peat moss had a significant positive effect on disease reduction compared to peat substrate (control)	Moustafa et al. 1977
Hardwood bark (HBC) and pine bark (PB)	*Phytophthora*, *Pythium. Thielaviopsis* root rots, *Rhizoctonia* damping-off and *Fusarium* wilt		All five diseases were suppressed with HBC; however, PB suppressed *Phytophthora* and *Pythium* but not *Rhizoctonia*	Hoitink 1980
Liquorice roots (LRC)	*Pythium aphanidermatum*	Cucumber	LRC substituted at 50% (v/v) for peat moss resulted in a 53% reduction in diseased plants compared with unmixed peat substrate (control)	Hadar and Mandelbaum 1986
Hardwood bark (HBC)	*Pythium ultimum*	Cucumber	HBC substituted at 50% (v/v) for peat moss resulted in a 63% reduction in diseased plants compared with unmixed peat substrate (control)	Chen et al. 1987
Hardwood bark (HBC)	*Pythium ultimum*	Cucumber	HBC pile (high temperature, $> 60°C$) was conducive and after 3–4 days at 25°C became suppressive. Suppression was due to mesophilic organisms, great microbial activity, and low levels of nutrients. Importance of microbiostasis	Chen et al. 1988
Composted grape marc (GMC) and composted separated cattle manure (CSM)	*Rhizoctonia solani* *Sclerotium rolfsii*	Radish plants, pothos, bean and chickpea	Media containing GMC or CSM were suppressive to diseases caused by *Rhizoctonia solani and Sclerotium rolfsii*	Gorodecki and Hadar 1990
Peat with different levels of decomposition and bark	*Pythium ultimum*	Cucumber	Suppressiveness of the disease can be predicted by microbial activity	Inbar et al. 1991

Peat mixtures (peat:perlite, 1:1, v/v) with different levels of decomposed light and dark peat	*Pythium ultimum*	Cucumber	The most decomposed dark peat was less suppressive than the less decomposed light peat mixed (1:1, v/v) with perlite). Results suggest that suppression is biological in origin	Boehm and Hoitink 1992
Spruce bark (SBC)	*Pythium ultimum*	Cucumber	Unmixed SBC resulted in 20% reduction in diseased plants compared with peat	Zhang et al. 1996
Cattle manure (CMC)	*Pythium aphanidermatum*	Cucumber	CMC substituted at 66% (v/v) for peat moss resulted in a 85% reduction in diseased plants compared with unmixed peat substrate (control)	Mandelbaum and Hadar 1997
Vegetable fruit and garden waste (VFG)	*Rhizoctonia solani*	Cucumber	Mature VFG (5–7 months) substituted at 20% (v/v) in peat: perlite mixtures was more suppressive than VFG with shorter period of maturity (1 month) Origin and age of compost is important in this disease suppression.	Tuitert et al. 1998
Bark (BC)	*Pythium ultimum*	Pea	BC substituted at 30% (v/v) for peat moss resulted in a 75% reduction in diseased plants compared with unmixed peat substrate (control)	Erhart et al. 1999
Composted grape marc (CGM)			CGM substituted at 30% (v/v) for peat moss resulted in a 30% increase in diseased plants compared with unmixed peat substrate (control)	
Vegetable, fruit, green waste (VFC)	*Pythium ultimum*	Cucumber	VFC substituted at 20% (v/v) for peat moss resulted in a 71% reduction in diseased plants compared with unmixed peat substrate (control)	Ryckeboer 2001

(*Continued*)

Table 3 – *continued*

Compost materials	Phytopathogens	Crop plant	Summarised effects	References
Green waste (GWC)	*Rhizoctonia solani*	Radish	GWC substituted at 20% (v/v) resulted in a 65% reduction in diseased plants compared with unmixed peat substrate (control)	Ryckeboer 2001
Vegetable, fruit, green waste (VFC)	*Rhizoctonia solani*	Radish	No significant difference in disease incidence in PBS compared with VFC substituted at 20% (v/v)	Ryckeboer 2001
Sewage sludge (SS), green waste (GW)	*Fusarium oxysporum f. sp. lycopersici*	Tomato	SS and GW substituted at 10% (v/v) resulted in a 54% reduction in diseased plants compared with unmixed peat substrate (control)	Cotxarrera et al. 2002
Green, vegetable wastes, horse manure (GHC)	*Pythium ultimum*	Cress	GHC substituted at 33% (v/v) for peat moss resulted in a 60% reduction in diseased plants compared with unmixed peat substrate (control)	Fuchs 2002
Pulp and paper mill	*Fusarium oxysporum f.sp. radicis lycopersici*	Tomato	*Pythium oligandrum* enriched composts induced histological and cytological changes near the pathogen ingress	Pharand et al. 2002
Composted grape marc (GMC) and cork compost (CC)	*Fusarium oxysporum f.sp. lycopersici*	Tomato	Peat and vermiculite were conducive to the disease, GMC was most suppressive, and CC had an intermediate suppressive effect. Important factors affecting suppressivity are of pH, glucosidase activity, and microbial populations	Borrero et al. 2004
Cork compost (CC) and light peat	*Verticillium dahliae*	Tomato	Cork compost had higher microbial activity and biomass and was suppressive in comparison with peat. The carbon metabolic profiles differed between plant growth media.	Borrero et al. 2005

18 composts from different countries	*Verticillium dahliae* (eggplants), *Rhizoctonia solani* (cauliflower and pinus), *Phytophthora nicotianae* (tomato) *Phytophthora cinamomi* (lupin), *Cylindrocladium spathiphylli* (spathiphyllum); *Fusarium oxysporum f.sp. lini* (flax)		Across compost types, the most consistent disease suppression (64–71%) was found against *F. oxysporum* and the most infrequent (4.7–6.5%) was against *P. cinnamomi* and *R. solani.*	Termorshuizen et al. 2006
Cork compost (CC), olive marc compost (OC), composted grape marc (GMC), spent mushroom compost (SMC)	*Rhizoctonia solani*	Cucumber	Disease incidence reduction of 53% in CC (0.5–1-year age) and in OC, GMC, and SMC (1.5–3 year age) in comparison to peat-based substrate (PBS)	Trillas et al. 2006
Mature biosolids compost (sewage sludge and yard waste)	*Sclerotinia rolfsii*	Bean	Suppressiveness is greatly reduced with prolonged compost curing. Combination of microbial populations and the chemical environment were responsible for pathogen suppression	Danon et al. 2007
Grape marc and extracted olive press cake, olive tree leaves and olive mill waste water, and spent mushroom compost	*Fusarium oxysporum f.sp. radicis lycopersici*	Tomato	High levels of suppressivity were achieved with all three composts. Suppression was related to the presence of specific microorganisms.	Ntougias et al. 2008, Kavroulakis et al. 2010
Compost from viticulture (VC), organic fraction differentiated of municipal bio-waste (MB) (DMB), or undifferentiated of MB (UMB), MB + cow manure (MBC) and peat and differentiated MB (1: 1, v/v) (PDMB)	*Pythium ultimum, Rhizoctonia solani* and *Sclerotinia minor*	Garden cress	All composts were more effective at reducing damping-off caused by the phytopathogens than were peat alone control. The most effective composts against *P. ultimum* were DMB, MBC, and PDMB. The best composts against *R. solani* were VC and MBC. The best compost against *S. minor* was DMB.	Pane et al. 2011

et al. (1999) demonstrated that compost prepared from grape marc or "biowaste" had neutral or promoting effects on *Pythium* rot diseases. However, Hadar and Gorodecki (1991) reported that compost made from grape pomace, which contains high concentrations of sugars and relatively low levels of cellulosic substances, tends to become colonized by *Aspergillus* and *Penicillium* spp., which have been shown to suppress *Sclerotium rolfsii*. Reports also have shown that compost made from lignocellulosic substances such as tree barks consistently suppress *Pythium* root rot (Hoitink 1980; Kuter et al. 1983). In such studies, attempts have been made to link suppressivity of compost teas to biological attributes such as microbial diversity and populations or the presence of specific microorganisms.

Besides the selection of feedstock for their potential disease suppressive properties, investigations have been conducted on producing disease suppressive compost from materials that are readily available locally using various composting systems and protocols. For example, Nakasaki et al. (1998) demonstrated that disease suppressive compost could be produced from grass clippings using a bench-scale composting system by controlling composting temperatures and inoculating the compost with *Bacillus subtilis* N4 at specific times. In such studies, particular emphasis is placed on modelling the evolution of key physico-chemical parameters such as temperature, nutrient balance (C:N ratio), nitrogen, pH, moisture content, carbon loss, and electrical conductivity during composting. These models served as important monitoring or management tools, which provide information on the consistency of the composting process and identify specific times for interventions. For example, Hoitink et al. (1991) used the peak heating period and/or thermophilic phase as identified by temperature models or graphs as a time marker after which *Trichoderma hamatum* 382 and *Flavobacterium balustinum* 299 were inoculated into compost so as to consistently induce suppression of diseases caused by a broad spectrum of soil-borne plant pathogens. The evaluation of the peak heating period for temperatures $> 55°C$ for at least three days has become an industry process standard or protocol, which implies that most plant and human pathogens have been killed (Rynk 1992).

An assessment of the degree of maturity of compost and organic matter decomposition level also has been deemed crucial in determining disease suppressiveness of compost. De Ceuster and Hoitink (1999) noted that fresh organic matter does not usually support biological disease control, even if it is inoculated with microbial species/strains of proven efficacy. It is generally accepted that immature compost frequently contains toxic compounds, which affect the growth of crop and pre-dispose them to attack by pests and pathogens (Hoitink and Boehm 1999; Hoitink et al. 1993), and the addition of older, more humidified peats to composted bark reduces or eliminates suppressivity due to its inability to support the activity of biological control agents (Boehm and Hoitink 1992). However, a recent review paper by Bonanomi et al. (2010) showed that during organic matter decomposition, disease suppression potential increased, decreased, was unchanged, or showed more complex responses, such as "hump-shaped" dynamics with compost of decreasing organic matter content. They found that the most useful features for predicting disease suppressiveness were fluorescein diacetate (FDA) activity, substrate respiration, microbial biomass, total culturable bacteria, fluorescent pseudomonads, and *Trichoderma* populations.

Pane et al. (2011), however, found that the most useful parameters to predict disease suppression were different for each pathogen: extractable carbon, *O*-aryl C and C:N ratio for *P. ultimum*, alkyl/*O*-alkyl ratio, *N*-acetyl-glucosaminidase and chitobiosidase enzymatic activities for *R. solani* and EC for *S. minor*. As it concerns the chemical properties of compost, Hoitink et al. (1996) reported that highly saline composts enhance

Pythium and Phytophthora diseases unless they are applied months ahead of planting to allow leaching. The dilution of highly saline compost by producing compost teas may allow for the lower or absence of phytotoxicity while still retaining disease suppressive properties of the compost.

Compost teas as a plant disease control agent

Table 4 provides a summary of the relatively few studies done on the efficacy of compost teas (aerated or non-aerated) in suppressing soil-borne diseases in soil-less or containerized production of vegetable crops. Liping et al. (1999, 2001) reported effective control of *Fusarium* wilt of greenhouse grown cucumber (*F. oxysporum* f. sp. *cucumerinum*) and sweet pepper (*F. oxysporum* f. sp. *vasinfectum*) using drench applications of NCT made from pig, horse, and cow manures. They found that NCT had a mycolytic effect on *Fusarium* chlamydospores and microspores which suggested that disease suppression was achieved through the destruction of the propagules of the pathogen.

Investigations done by Scheuerell and Mahaffee (2004) showed that the development of *Pythium* damping-off of cucumber grown in soil-less media was significantly reduced by the application of aerated and non-aerated compost teas, with aerated compost teas fermented with kelp and humic acid nutrients displaying the most consistent disease suppression. Diánez et al. (2006, 2007) reported that nine fungi including *Rhizoctonia solani* and *Pythium aphanidermatum* were controlled *in vitro* using ACT made from grape marc compost. They demonstrated that the growth inhibition of nine of the fungi tested was the result of siderophores excreted by microorganisms present in the grape marc compost. Siddiqui et al. (2009) reported that non-sterilized ACT made from rice straw (RST) and empty fruit bunch (EFB) of oil palm composts inhibited conidial germination of *Choanephora cucurbitarum*, the causal pathogen for wet rot of okra. They also reported that induced host resistance was stimulated in okra plants treated with non-sterilized and filter-sterilized compost teas during glass house trials. However, resistance was not maintained as it decreased with time, probably due to a highly stressed environment.

The results from these studies indicate that compost teas as soil drenches may be an effective control strategy for root diseases in soil-less production systems. However, further research is needed to obtain a greater understanding of the factors affecting suppressivity of compost teas and mechanisms used to effect control. This may prove useful in assessing the utility of *in vitro* pathogen screening results as predictors of disease suppression under *in vivo* and in-field conditions. As it stands, testing compost teas for soil-borne disease suppression under simulated field conditions, with the crop growing in pathogen-inoculated soil or growing media, might be a better predictor of field suppression than *in vitro* assays (Scheuerell and Mahaffee 2002).

Factors affecting disease suppression induced by compost teas

As with compost, the maturity and source of compost used to make the compost teas have been shown to affect the suppressivity of the teas (Siddiqui et al. 2009; Tränkner 1992). Compost tea production factors such as aeration, fermentation time, and nutrients have all been reported to affect the biological properties of the teas (Litterick and Wood 2009). For example, Ingham and Alms (2003) stated that ACT are generally more effective than NCT because they tend to have higher microbial populations and diversity. Conversely, the majority of scientific literature supports the suppression of phytopathogens by NCT.

Table 4. Summary of container and *in vitro* experiments examining the use of compost teas and extracts to suppress soil-borne diseases in vegetable crops.

Brewing method[a]	Crop	Phytopathogens	Control[b]	Compost type	Brewing duration	Brewing nutrients	Reference
NCT	Tomato	*Phytophthora intestans*	+	Horse-straw-soil	14 days	None	Ketterer 1990
NCT	IV[c]	*Rhizoctonia solani*	+	–	–	None	Weltzien 1991
NCT	Tomato	*Phytophthora intestans*	+	Not stated	7–14 days	None	Ketterer and Schwager 1992
NCT	Pea	*Pythium ultimum*	+	Cattle manure or grape marc	5–10 days	None	Tränkner 1992
			+				
Compost extract	Sweet pepper	*Fusarium oxysporum f.sp. vasinfectum*	+	Pig, horse, and cow manures	No brewing (NB)	None	Liping et al. 2001
Compost extract		*Pythium debaryanum, Fusarium oxysporum f.sp. lycopersici, Sclerotium bataticola*	+	Leafy fruit compost (LFC), garden compost (GC), and crops compost (CC)	NB	None	El-Masry et al. 2002
			+				
			+				
ACT	Cucumber	*Pythium ultimum*	+	Yard trimmings, mixed vegetation (vermicompost), vegetative and animal manure-based composts	36 hours	Kelp and humic acid	Scheuerell and Mahaffee 2004
NCT			+		7–9 days	Bacterial or fungal additive[d]	

ACT	IV	*Rhizoctonia solani, Fusarium oxysporum* f. sp. *radicis-lycopersici, F. oxysporum* f. sp. *lycopersici race 0, F. oxysporum* f. sp. *lycopersici race 1, F. oxysporum* f. sp. *radicis-cucumerinum, Verticillium dahliae, Pythium aphanidermatum, Phytophthora parasitica* and *Verticillium fungicola*	+	Grape marc	24 h	None	Diánez et al. 2006
			+ + + + + + + +				
Compost extract	IV	*Fusarium oxysporum* f. sp. *Radices-lycopersici*, *F. solani, F. graminearum, Sclerotinia sclerotiorum, Rhizoctonia solani, R. bataticola, Pythium* sp. *Verticillium dahliae*	+	Cattle manure, sheep manure, vegetable based, ground straw	NB	None	Kerkeni et al. 2007
Compost extract	Okra	*Choanephora* cucurbitarum[(4)]	+	Rice straw and empty fruit bunch of oil palm	none	*Trichoderma* enriched	Siddiqui et al. 2008
			+				

(*Continued*)

Table 4 – *continued*

Brewing method[a]	Crop	Phytopathogens	Control[b]	Compost type	Brewing duration	Brewing nutrients	Reference
Compost extract	IV	*Sclerotium rolfsii*	+	–	NB	None	Zmora-Nahum et al. 2008
Compost extract (NCT)	Tomato	*Pythium aphanidermatum*	+	Solid olive mill wastes (SOMW), *Posidonia oceanica* (Po), and chicken manure (CM),	6 days	None	Jenana et al. 2009
			+				
			+				
ACT	Okra	*Choanephora cucurbitarum*	+	Rice straw and empty fruit bunch of oil palm	none	None	Siddiqui et al. 2009
			+				
NCT	IV	*Phytophthora infestans*	+	Chicken manure, sheep manure (four sources; SM1–SM4), bovine manure, shrimp powder, or seaweed	14 days	None	Koné et al. 2010
Compost extract	Pepper	*Phytophthora capsici*	+	Six types of commercial compost mixes	30 min	None	Sang et al. 2010
Compost extract	IV	*Rhizoctonia solani*	–	Pig manure and straw compost	–	None	Xu et al. 2012
ACT			–				
NCT			–				

Note: [a] Brewing method; NCT = non-aerated compost teas; ACT = aerated compost teas.
[b] Control: + treatments statistically less disease (minimum $p = 0.05$) than control treatment; - treatment no difference from control treatment
[c] Experimental scale: IV = *in vitro*,
[d] Bacterial additive: 5 ml of Bacterial Nutrient Solution (Soil Soup Inc., Edmonds (WA)); fungal additive: 1.2 g of Maxicrop soluble seaweed powder (Maxicrop USA Inc., Arlington Heights (IL)), 2.5 ml of Humax liquid humic acids (JH Biotech Inc., Ventura (CA)), 3 g of rock dust (Target Glacial Dust; Target Products Ltd., Burnaby, B.C. (Canada)).

A comparison of the efficacy of ACT and NCT within the same study has often shown that aeration has no effect on disease control (Scheuerell and Mahaffee 2006), implying that the mechanism of disease control is chemical in nature rather than biological.

Disease suppressive properties of NCT and ACT have generally been reported to increase with fermentation time to a maximum and then decline (Ketterer 1990; Ketterer and Schwager 1992). According to Ingham and Alms (2003), optimum fermentation time is usually between 18 and 36 h at the point where active microbial biomass is at its highest. Conversely, other investigators have suggested that fermentation times of 7 to 14 days are better when producing compost teas with optimal disease suppressive properties (Weltzien 1990). Although not substantiated by data, it is generally thought that optimum time is likely to depend on the compost source and fermentation method (Litterick and Wood 2009).

Disease suppressive properties of compost teas have been enhanced (Scheuerell and Mahaffee 2006), reduced (Scheuerell and Mahaffee 2004), or shown no significant change (Elad and Shtienberg 1994) with the addition of nutrients. Nutrients are primarily added to increase overall microbial populations or the population of a specific group of microorganisms that are thought to have beneficial effects. Whilst the addition of nutrients may enhance the disease suppressive properties of compost teas, there are mounting concerns on the regrowth potential of human pathogens in teas (National Organic Standards Board 2011; Yohalem et al. 1994). However, recent investigations have shown that pathogen regrowth does not appear to be supported in compost tea fermentation that does not contain added nutrients (Brinton et al. 2004; Duffy et al. 2002).

Compost tea application factors such as dilution rate, application frequency, and use of adjuvants also have been reported to affect the efficacy of teas to suppress plant diseases (Litterick and Wood 2009). Of primary importance for soil-borne disease investigations are dilution and application frequency for which there are very few published studies. Reports have shown that the disease suppressive properties of compost teas were either maintained or decreased after dilution (Elad and Shtienberg 1994; Scheuerell and Mahaffee 2004). However, more studies on dilution and application frequency are needed to determine whether compost teas can be used economically on a large scale.

Mechanisms involved in the suppression of plant disease by compost and compost teas

Most scientific literature has shown that the disease suppressive effect of composts is lost following sterilization or pasteurization (Cotxarrera et al. 2002; Hoitink et al. 1996; Van Beneden et al. 2010). El-Masry et al. (2002) found that the water extracts from several composts were suppressive to several soil-borne pathogens, but the extracts did not contain antibiotics or siderophores. These results have been used to indicate that, in most instances, the suppressive effect of compost is predominantly biological rather than chemical or physical in nature (Baker and Paulitz 1996; Joshi et al. 2009). To this end, four mechanisms have been described through which biological control agents (BCAs) suppress plant pathogens: antibiosis, competition for nutrients, parasitism or predation, and induced systemic resistance (Hoitink and Fahy 1986). Most reports suggest that microbiostasis (antibiosis and/or competition for nutrients) and hyperparasitism are the principal mechanisms by which plant pathogens are suppressed.

Antibiosis refers to an association between organisms where the production of specific and/or non-toxic specific metabolites or antibiotics by one organism has a direct effect on other organisms (Litterick and Wood 2009). For example, Chernin et al. (1995) reported that chitinolytic enzymes produced by *Enterobacter* strains were found to be antagonistic to several fungal pathogens including *Rhizoctonia solani*. The toxin "gliotoxin" isolated from *Gliocladium virens* was found to be antagonistic against *P. ultimum* (Lumsden et al. 1992; Roberts and Lumsden 1990). Antagonistic activity of bacteria and fungi from horticultural compost against other plant pathogens including *F. oxysporum* also has been reported (Suarez-Estrella et al. 2007).

Competition results when there is a demand by two or more microorganisms for a resource. It occurs when a non-pathogen successfully out-competes a plant pathogen for a resource which may lead to disease control (Litterick and Wood 2009). For example, some microorganisms reduce the disease incidence by limiting iron availability for pathogens such as *Pythium* spp. through the production of low molecular weight ferric-specific ligands (siderophores) under iron limiting conditions (Sivan and Chet 1989; Srivastava et al. 2010). Suppression by microbiostasis seems to be more effective against pathogens with propagules < 200 μm diam. including *Phytophthora* and *Pythium* spp. (Hoitink and Ramos 2008).

In contrast, parasitism has been observed with plant pathogens with propagules > 200 μm diam. The parasitic effect which has been observed in $< 20\%$ of uninoculated composts (Hoitink et al. 1996) consists of four stages: chemotrophic growth, recognition, attachment, and degradation of the host cell walls through the production of lytic enzymes (Woo et al. 2006). All of these stages are affected by the organic matter decomposition level and the presence of glucose and other soluble nutrients, which repress the production and effect of lytic enzymes used to kill pathogens (Hoitink et al. 1996).

Induced systemic resistance (ISR) triggered by beneficial microorganisms also has been proven to reduce disease severity in many crops (De Clercq et al. 2004; Khan et al. 2004). For example, Lievens et al. (2001) showed that composts can induce systemic resistance to *Pythium* root-rot in cucumber when applied to a section of the root system using a split root system. Similar results have been reported by other authors, who have isolated microorganisms from compost which trigger the systemic resistance effect (Hoitink et al. 2006; Horst et al. 2005). Most studies on ISR have involved the use of *Trichoderma* spp., microorganisms also known for their mycoparasitic and antibiosis effects (Hoitink et al. 2006; Khan et al. 2004).

To this end, the four suppression mechanisms also have been loosely divided into two categories: general and specific (Cook and Baker 1983). General refers to disease suppression which can be attributed to the activity of many different types of microorganisms. Suppression usually results from the competition for nutrients and ecological niches by numerous bacterial and fungal species that adversely affect the activity of, or induce microbiostasis of, plant pathogens (Litterick and Wood 2009). Specific refers to a situation where suppression of a pathogen or the disease it causes can be attributed to the presence and/or activity of one or two microorganisms. Reports showed that $> 90\%$ of the composts studied suppress disease through the general mechanisms rather than the specific. However, the disease suppressive effects resulting from general mechanisms are not easily transferable from one medium to another.

Conclusions and future work

Despite the increasing amount of information regarding compost as plant growth substrates, and compost and compost tea as plant disease suppressive agents, the overarching challenge remains integrating findings into commercial vegetable production systems. An important step toward application of suppressive compost and compost tea could be the development of quality control tools that may reduce the variability in efficacy (Hadar 2011). Unfortunately, there is no single chemical or physical, easy-to-perform parameter that could predict suppression, therefore quality control is dependent on bioassays designed for a specific pathogen or disease (Hadar 2011). This clearly emphasises the need for a better understanding of the mechanisms and antagonistic microorganisms involved in disease suppression.

Some of the new techniques based on organic matter characterization or assessment of microbial diversity or functional diversity using a combination of DNA-based techniques such as analysis of terminal restriction fragment length polymorphisms (T-RLFPs) (Michel et al. 2002) and denaturing gradient gel electrophoresis (DGGE) (Calvo-Bado et al. 2003) may lead to an improved understanding of the changes in microbial communities associated with disease control resulting from compost or compost tea application to various media (Litterick and Wood 2009; Noble and Coventry 2005). Such studies also will assist in the development of protocols for optimizing the compost tea production process so as to maximize disease suppressive effect without exposing the manufacturer or user to the risk of human pathogens (Ingram and Millner 2007). To achieve consistent disease suppression, it may be necessary to modify compost tea production steps, for example, by the addition of nutrient amendments to ensure the growth of specific groups of microbes (Scheuerell and Mahaffee 2002). However, there is a need to test nutrient supplements for their effect on both targeted plant pathogens and non-targeted human pathogens (Scheuerell and Mahaffee 2002). To date, molasses has been demonstrated to support the growth of *Escherichia coli* and *Salmonella* if inadvertently present in compost tea, posing worker and consumer health concerns (Bess et al. 2002; Duffy et al. 2004). Further studies are needed on the interaction between aeration and fermentation nutrients for optimising disease suppression.

Studies aimed at developing compost from locally available waste materials other than pine bark, which has the potential to consistently suppress soil-borne pathogens and serves as a replacement medium for peat-based products, are needed. It may be necessary to inoculate these composts with biological control agents which may improve the efficacy and reliability of disease control obtained (Nakasaki et al. 1998; Scheuerell and Mahaffee 2002). To this end, it is recommended that compost and compost tea must be used as part of an integrated disease management system with other strategies, including genetic disease resistance, fertility and water management, disease and pest forecasting, and other cultural approaches to enhance plant health (Mahaffee and Scheuerell 2006).

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References

Abad M, Martínez PF, Martínez MD, Martínez J. 1993. Evaluación agronómica de los sustratos de cultivo [Agronomic evaluation of growth substrates]. Actas Hortic. 11:141–154.

Acurio G, Rossin A, Teixeira F, Zepeda F. 1998. Diagnosis of municipal solid waste management in Latin America and the Caribbean. Washington (DC): Pan American Health Organization (PAHO).

Alexander PD. 2009. An assessment of the suitability of backyard produced compost as a potting soil. Compost Sci. Util. 17:74–84.

Ali M, Griffiths AJ, Williams KP, Jones DL. 2007. Evaluating the growth characteristics of lettuce in vermicompost and green waste compost. Eur. J. Soil Biol. 43:S316–S319.

Baker R, Paulitz TC. 1996. Theoretical basis for microbial interactions leading to biological control of soilborne plant pathogens. In: Hall R, editor. Principles and practice of managing soilborne plant pathogens. St. Paul (MN): The American Phytopathological Society. p. 50–79.

Ball AS, Shah D, Wheatley CF. 2000. Assessment of the potential of a novel newspaper/horse manure-based compost. Bioresour. Technol. 73:163–167.

Bardhan S, Yona C, Dick WA. 2009. Recycling for sustainability: Plant growth media from coal combustion products, biosolids and compost. Int. J. Environ. Sci. Eng. 1:176–182.

Berecha G, Lemessa F, Wakjira M. 2011. Exploring the suitability of coffee pulp compost as growth media substitute in greenhouse production. Int. J. Agric. Res. 6:255–267.

Bernal MP, Alburquerque JA, Moral R. 2008. Composting of animal manures and chemical criteria for compost maturity assessment. A review. Biores. Technol. 100:5444–5453.

Bess VH, Manes RBS, Snodgrass JL. 2002. *E. coli* survival in compost tea using different nutrient substrates. In: Michel FC, Rynk RF, Hoitink HAJ, editors. Proceedings of the 2002 International Symposium Composting and Compost Utilization. Emmaus (PA): JG Press. p. 1150–1157.

Boehm MJ, Hoitink HAJ. 1992. Sustenance of microbial activity in potting mixes and its impact on severity of *Pythium* root rot of poinsettia. Phytopathol. 82:259–264.

Bonanomi G, Antignani V, Capodilupo M, Scala F. 2010. Identifying the characteristics of organic soil amendments that suppress soilborne plant diseases. Soil Biol, Biochem. 42:136–144.

Bonanomi G, Antignani V, Pane C, Scala F. 2007. Suppression of soilborne fungal diseases with organic amendments. J. Plant Pathol. 89:311–324.

Borrero C, Castillo S, Ordovas J, Tello JC, Avilés M. 2005. Composted cork as suppressive substrate to *Verticillium* wilt of tomato. In: Michel FC, Rynk RF, Hoitink HAJ, editors. Proceedings of the 2002 International Symposium Composting and Compost Utilization. Emmaus (PA): JG press. p. 1342–1352.

Borrero C, Trillas MI, Ordovbs J, Tello JC, Avilqs M. 2004. Predictive factors for the suppression of *Fusarium* wilt of tomato in plant growth media. Phytopathol. 94:1094–1101.

Boulter JI, Boland GJ, Trevors JT. 2000. Compost: A study of the development process and end-product potential for suppression of turfgrass disease. World J. Microbiol. Biotechnol. 16:115–134.

Brinton W, Storms P, Evans E, Hill J. 2004. Compost teas: Microbial hygiene and quality in relation to method of preparation. J. Biodyn. 2:36–45.

Brinton WF. 2000. Compost quality standards and guidelines: An international view. Final report by Woods End Research Laboratory for the New York State Association of Recyclers [Internet]. [cited 2011 June 27]. Available from: http://solvita.com/pdf-files/nysar-ne.pdf

Brinton WF, Tränkner A, Droffner M. 1996. Investigations into liquid compost extracts. BioCycle. 37:68–70.

Brito LM, Coutinho J, Smith SR. 2008. Methods to improve the composting process of the solid fraction of dairy cattle slurry. Bioresour. Technol. 99:8955–8960.

Buchanan M, Gliessman SR. 1991. How compost fertilization affects soil nitrogen and crop yield. BioCycle. 32:72–77.

Bustamante MA, Moral R, Agulló E, Pérez-Murcia MD, Pérez-Espinosa A, Medina EM, Paredes C. 2009. Use of winery-distillery composts for lettuce and watermelon seedling production. Acta Hort. (ISHS). 898:143–150.

Bustamante MA, Paredes C, Moral R, Agulló E, Pérez-Murcia MD, Abad M. 2008. Composts from distillery wastes as peat substitutes for transplant production. Resour. Conserv. Recycl. 52:792–799.

Calvo-Bado LA, Morgan JAW, Sergeant M, Pettitt TR, Whipps JM. 2003. Molecular characterization of Legionella populations present within slow sand filters used for fungal plant pathogen suppression in horticultural crops. Appl. Environ. Microbiol. 69:533–541.

Cayne BS, Lechner D. 1989. The new Lexicon Webster's dictionary of the English language. New York (NY): Lexicon.

Ceglie FG, Elshafie H, Verrastro V, Tittarelli F. 2011. Evaluation of olive pomace and green waste composts as peat subsitutes for organic tomato seedling production. Compost Sci. Util. 19:293–300.

Chaney RL, Ryan JA. 1993. Heavy metals and toxic organic pollutants in MSW-composts: Research results on phytoavailability, bioavailability, etc. In: Hoitink HAJ, Keener HM, editors. Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization aspects. Worthington (OH): Renaissance Publications. p. 451–506.

Chen W, Hoitink HAJ, Madden LV. 1988. Microbial activity and biomass in container media for predicting suppressiveness to damping-off caused by *Pythium ultimum*. Phytopathol. 78:1447–1450.

Chen W, Hoitink HAJ, Schmitthenner AF. 1987. Factors affecting suppression of *Pythium* damping-off in container media amended with composts. Phytopathol. 77:755–760.

Chernin L, Ismailov Z, Haran S, Chet I. 1995. Chitinolytic Enterobacter agglomerans antagonistic to fungal plant pathogens. Appl. Environ. Microbiol. 61:1720–1726.

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

Cook RJ, Baker KF. 1983. The nature and practice of biological control of plant pathogens. St. Paul (MN): American Phytopathological Society.

Cotxarrera L, Trillas-Gay MI, Steinberg C, Alabouvette C. 2002. Use of sewage sludge compost and Trichoderma asperellum isolates to suppress *Fusarium* wilt of tomato. Soil Biol. Biochem. 34:467–476.

Cronin MJ, Yohalem DS, Harris RF, Andrews JH. 1996. Putative mechanism and dynamics of inhibition of the apple scab pathogen Venturia inaequalis by compost extracts. Soil Biol. Biochem. 28:1241–1249.

Danon M, Zmora-Nahum S, Chen Y, Hadar Y. 2007. Prolonged compost curing reduces suppression of *Sclerotium rolfsii*. Soil Biol. Biochem. 39:1936–1946.

De Ceuster TJJ, Hoitink HAJ. 1999. Prospects for composts and biocontrol agents as substitutes for methyl bromide in biological control of plant diseases. Compost Sci. Util. 7:6–15.

De Clercq D, Vandesteene L, Coosemans J, Ryckeboer J. 2004. Use of compost as suppressor of plant diseases. In: Lens P, Hamelers B, Hoitink H, Bidlingmaier W, editors. Resource recovery and reuse in organic solid waste management. London (UK): IWA Publishing. p. 317–337.

Diánez F, Santos M, Boix A, de Cara M, Trillas I, Avilés M, Tello JC. 2006. Grape marc compost tea suppressiveness to plant pathogenic fungi: Role of siderophores. Compost Sci. Util. 14:48–53.

Diánez F, Santos M, Tello JC. 2007. Suppressive effects of grape marc compost on phytopathogenic oomycetes. Arch. Phytopathol. Plant Prot. 40:1–18.

Diaz LF, de Bertoldi M, Bidlingmaier W. 2007. Compost science and technology. 8th ed. Amsterdam (The Netherlands): Elsevier Science.

Diaz-Perez JC, Granberry DM, Germishuizen P. 2006. Transplant growth and stand establishment of bell pepper (*Capsicum annuum* L.) plants as affected by compost-amended substrate. Acta Hort. 782:223–228.

Diaz-Perez M, Camacho-Ferre F. 2010. Effect of composts in substrates on the growth of tomato transplants. Hort Technol. 20:361–367.

Díaz-Pérez M, González F, Moreno O, Camacho F. 2009. Use of composts from municipal wastes as substrates to produce tomato and melon seedlings in nurseries. Acta Hort. (ISHS). 898:159–163.

Duffy B, Sarreal C, Ravva S, Stanker L. 2004. Effect of molasses on regrowth of *E. coli* O157: H7 and *Salmonella* in compost teas. Compost Sci. Util. 12:93–96.

Duffy B, Sarreal C, Stevenson R, Subbarao R, Stanker L. 2002. Regrowth of pathogenic bacteria in compost teas and risk of transmission to strawberry plants. In: Michel FC, Rynk RF, Hoitink HAJ, editors. Proceedings of the 2002 International Symposium Composting and Compost Utilization. Emmaus (PA): JG Press. p. 1142–1149.

Dziejowski JE, Kazanowska J. 2002. Heat production during thermophilic decomposition of municipal wastes in the Dano-system composting plant. In: Insam H, Riddech N, Klammer S, editors. Microbiology of composting. Berlin (Germany): Springer-Verlag. p. 111–118.

El-Masry MH, Khalil AI, Hassouna MS, Ibrahim HAH. 2002. *In situ* and *in vitro* suppressive effect of agricultural composts and their water extracts on some phytopathogenic fungi. World J. Microbiol. Biotechnol. 18:551–558.

Elad Y, Shtienberg D. 1994. Effect of compost water extracts on grey mould (*Botrytis cinerea*). Crop Prot. 13:109–114.

Epstein E. 1997. The science of composting, part 1. Lancaster (PA): Technomic Pub. Co.

Erhart E, Burian K, Hartl W, Stich K. 1999. Suppression of *Pythium ultimum* by biowaste composts in relation to compost microbial biomass, activity and content of phenolic compounds. J. Phytopathol. 147:299–305.

Fitzpatrick GE. 2001. Compost utilization in ornamental and nursery crop production systems. In: Stoffella PJ, Kahn BA, editors. Compost utilization in horticultural cropping systems. Boca Raton (FL): Lewis Publishers. p. 135–149.

Fröhlich M, Hechenbichler G, Hundsberge S, Ortner M, Baumgartner A. 1993. Kompostqualität: Anwendungsformern—Güteklassen [Compost Quality—Application Classes] in Handbuch der Kompostierung. Vienna (Austria): Austrian Ministry for Agriculture and Forestry.

Fuchs JG. 2002. Practical use of quality compost for plant health and vitality improvement. In: Insam H, Riddech N, Klammer S, editors. Microbiology of composting. Berlin (Germany): Springer-Verlag. p. 435–444.

Ghanbari Jahromi M, Aboutalebi A. 2009. Garden compost as a substrate for vegetable transplant production. Acta Hort. (ISHS). 898:165–170.

Golueke CG. 1982. When is compost "safe"? A review of criteria for assessing the destruction of pathogens in composting. BioCycle. 28:28–38.

Gonani Z, Riahi H, Sharifi K. 2011. Impact of using leached spent mushroom compost as partial growing media for horticultural plants. J. Plant Nutr. 34:337–344.

Gorodecki B, Hadar Y. 1990. Suppression of *Rhizoctonia solani* and *Sclerotium rolfsii* diseases in container media containing composted separated cattle manure and composted grape marc. Crop Prot. 9:271–274.

Growing Solutions Incorporated. 2012. Compost tea systems [Internet]. Growing Solutions Incorporated [cited 2012 Feb 27]. Available from: http://www.growingsolutions.com/home/gs2/cpage_81/Compost%20Tea%20Systems.

Hadar Y. 2011. Suppressive compost: When plant pathology met microbial ecology. Phytoparasitica. 39:311–314.

Hadar Y, Gorodecki B. 1991. Suppression of germination of sclerotia of *Sclerotium rolfsii* in compost. Soil Biol. Biochem. 23:303–306.

Hadar Y, Inbar Y, Chen Y. 1985. Effect of compost maturity on tomato seedling growth. Sci. Hortic. 27:199–208.

Hadar Y, Mandelbaum R. 1986. Suppression of *Pythium aphanidermatum* damping-off in container media containing composted liquorice roots. Crop Prot. 5:88–92.

Hashemimajd K, Kalbasi M, Golchin A, Shariatmadari H. 2004. Comparison of vermicompost and composts as potting media for growth of tomatoes. J. Plant Nutr. 27:1107–1123.

Haug RT. 1993. The practical handbook of compost engineering. Boca Raton (FL): CRC Press.

Herrera F, Castillo JE, Chica AF, Lepez Bellido L. 2008. Use of municipal solid waste compost (MSWC) as a growing medium in the nursery production of tomato plants. Bioresour. Technol. 99:287–296.

Hoitink HAJ. 1980. Composted bark, a lightweight growth medium with fungicidal properties. Plant Dis. 64:142–147.

Hoitink HAJ, Boehm MJ. 1999. Biocontrol within the context of soil microbial communities: A substrate-dependent phenomenon. Annu. Rev. Phytopathol. 37:427–446.

Hoitink HAJ, Boehm MJ, Hadar Y. 1993. Mechanisms of suppression of soilborne plant pathogens in compost-amended substrates. In: Hoitink HAJ, Keener HM, editors. Science and engineering of composting: Design, environmental, microbiological and utilization. Worthington (OH): Renaissance. p. 600–621.

Hoitink HAJ, Fahy PC. 1986. Basis for the control of soilborne plant pathogens with composts. Annu. Rev. Phytopathol. 24:93–114.

Hoitink HAJ, Inbar Y, Boehm MJ. 1991. Status of compost-amended potting mixes naturally suppressive to soilborne diseases of floricultural crops. Plant Dis. 75:869–873.

Hoitink HAJ, Krause MS, Han DY. 2001. Spectrum and mechanisms of plant disease control with composts. In: Stofella PJ, Kahnn BA, editors. Compost utilization in horticultural cropping systems. Boca Raton (FL): Lewis Publishers. p. 263–274.

Hoitink HAJ, Madden LV, Dorrance AE. 2006. Systemic resistance induced by *Trichoderma* spp.: Interactions between the host, the pathogen, the biocontrol agent, and soil organic matter quality. Phytopathol. 96:186–189.

Hoitink HAJ, Ramos L. 2008. Impacts of composts on soil and plant health [Internet]. Wooster (OH): Ohio State University; [cited 2011 Jun 26]. Available from: http://plantpath.osu.edu/people-and-programs/faculty-directory/emeritus/hoitink-harry-a-j/hoitink-ramos-acorbat2008-3.doc.

Hoitink HAJ, Stone AG, Han DY. 1996. Suppression of plant diseases by composts. HortSci. 34:184–187.

Hornick SB, Sikora SB, Sterrett SB, Murray JJ, Millner PD, Burge WD, Colacicco D, Parr JF, Chaney RL, Willson GB. 1984. Utilization of sewage sludge compost as a soil conditioner and fertilizer for plant growth. Agric. Inform. Bull. No. 464. Washington (DC): U.S. Department of Agriculture, U.S. Government Printing Office.

Horst LE, Locke J, Krause CR, McMahon RW, Madden LV, Hoitink HAJ. 2005. Suppression of *Botrytis* blight of begonia by *Trichoderma hamatum* 382 in peat and compost-amended potting mixes. Plant Dis. 89:1195–1200.

Inbar Y, Boehm MJ, Hoitink HAJ. 1991. Hydrolysis of fluorescein diacetate in sphagnum peat container media for predicting suppressiveness to damping-off caused by *Pythium ultimum*. Soil Biol. Biochem. 23:479–483.

Ingham ER. 2000. Brewing compost tea. Kitchen Gardener. 29:16–19.

Ingham ER, Alms M. 1999. Compost tea manual. Corvallis (OR): Soil Foodweb, Inc.

Ingham ER, Alms M. 2003. The compost tea brewing manual. 4th ed. Corvallis (OR): Soil Foodweb.

Ingram DT, Millner PD. 2007. Factors affecting compost tea as a potential source of *Escherichia coli* and *Salmonella* on fresh produce. J. Food Prot. 70:828–834.

Jagdeo B. 2007. The Jagdeo Initiative. Tech. Inform. Bull. No.8. Georgetown (Guyana): The Private Sector Commission of Guyana Ltd.

Jayasinghe GY, Tokashiki Y, Arachchi ID, Arakaki M. 2010. Sewage sludge sugarcane trash based compost and synthetic aggregates as peat substitutes in containerized media for crop production. J. Hazard. Mater. 174:700–706.

Jenana RKBE, Haouala R, Ali M, Triki JJG, Hibar K, Ben M. 2009. Composts, compost extracts and bacterial suppressive action on *Pythium aphanidermatum* in tomato. Pak. J. Bot. 41:315–327.

Joshi D, Hooda KS, Bhatt JC, Mina BL, Gupta HS. 2009. Suppressive effects of composts on soil-borne and foliar diseases of French bean in the field in the western Indian Himalayas. Crop Prot. 28:608–615.

Kalantari S, Hatami S, Ardalan MM, Alikhani HA, Shorafa M. 2010. The effect of compost and vermicompost of yard leaf manure on growth of corn. Afr. J. Agric. Res. 5:1317–1323.

Kavroulakis N, Ntougias S, Besi MI, Katsou P, Damaskinou A, Ehaliotis C, Zervakis GI, Papadopoulou KK. 2010. Antagonistic bacteria of composted agro-industrial residues exhibit antibiosis against soil-borne fungal plant pathogens and protection of tomato plants from *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Plant Soil. 333:233–247.

Kerkeni A, Daami-Remadi M, Tarchoun N, Khedher MB. 2007. In vitro assessment of the antifungal activity of several compost extracts. Int. J. Agric. Res. 2:786–794.

Ketterer N. 1990. Untersuchungen zur wirkung von kompostextracten auf den blattbefall ser kartoffel und tomate durch *Phytophthora infestans* sowie auf den befall der weinrebe durch *Plasmopara viticola, Pseudopeziza tracheiphila* und *Uncinula necator* [Studies of the effect of compost extracts on potato and tomato leaf infections through Phytophthora infestans as well as the incidences of grape disease] [dissertation]. Bonn (Germany): University of Bonn.

Ketterer N, Schwager L. 1992. Effect of compost extracts on the disease incidence and the phyllosphere flora of bush bean and tomato leaves. Med. van de Fac. Land. Univ. Gent. 57:411–421.

Khan J, Ooka JJ, Miller SA, Madden LV, Hoitink HAJ. 2004. Systemic resistance induced by *Trichoderma hamatum* 382 in cucumber against *Phytophthora* crown rot and leaf blight. Plant Dis. 88:280–286.

Koné SB, Dionne A, Tweddell RJ, Antoun H, Avis TJ. 2010. Suppressive effect of non-aerated compost teas on foliar fungal pathogens of tomato. Biol. Control. 52:167–173.

Kuo S, Ortiz-Escobar ME, Hue NV, Hummel RL. 2004. Composting and compost utilization for agronomic and container crops. Recent Res. Dev. Environ. Biol. 1:451–513.

Kuter GA, Nelson EB, Hoitink HAJ, Madden LV. 1983. Fungal populations in container media amended with composted hardwood bark suppressive and conducive to *Rhizoctonia* damping-off. Phytopathol. 73:1450–1456.

Lazcano C, Arnold J, Tato A, Zaller JG, Domínguez J. 2009. Compost and vermicompost as nursery pot components: Effects on tomato plant growth and morphology. Span. J. Agric. Res. 7:944–951.

Lee KH. 1994. Effect of organic amendments and EM on the growth and yield of crops and on soil properties. In: Parr JF, Hornick SB, Simpson ME, editors. Proceedings of the Second

International Conference on Kyusei Nature Farming. Washington (DC): U.S. Department of Agriculture. p. 142–147.

Lievens B, Vaes K, Coosemans J, Ryckeboer J. 2001. Systemic resistance induced in cucumber against *Pythium* root rot by source separated household waste and yard trimmings composts. Compost Sci, Util. 9:221–229.

Liping MA, Gao F, Qiao XW. 1999. Efficiacy of compost extracts to cucumber wilt (*Fusarium oxysporum* f. sp. *cucumerinum*) and its mechanisms. Acta Phytopathol. Sin. 29:270–274.

Liping MA, Xiongwu Q, Fen GAO, Bianqing HAO. 2001. Control of sweet pepper *Fusarium* wilt with compost extracts and its mechanisms. Chinese J. Appl. Environ. Biol. 7:84–87.

Litterick A, Wood M. 2009. The use of composts and compost extracts in plant disease control. In: Walters D, editor. Disease control in crops: Biological and environmentally friendly approaches. Oxford (UK): Wiley-Blackwell. p. 93–121.

Litterick AM, Harrier L, Wallace P, Watson CA, Wood M. 2004. The role of uncomposted materials, composts, manures, and compost extracts in reducing pest and disease incidence and severity in sustainable temperate agricultural and horticultural crop production review. Crit. Rev. Plant Sci. 23:453–479.

Lohr VI, Ëbrien RG, Coffey DL. 1984. Spent mushroom compost in soilless media and its effects on the yield and quality of transplants. J. Am. Soc. Hort. Sci. 109:693–697.

Lumsden RD, Locke JC, Adkins ST, Walter JF, Ridout CJ. 1992. Isolation and localization of the antibiotic gliotoxin produced by *Gliocladium virens* from alginate prill in soil and soilless media. Phytopathol. 82:230–235.

Lwin M, Ranamukhaarachchi SL. 2006. Development of biological control of *Ralstonia solanacearum* through antagonistic microbial populations. Int. J. Agric. Biol. 8:657–660.

Mahaffee WF, Scheuerell SJ. 2006. Compost teas: Alternative approaches to the biological control of plant diseases. In: Bailey MJ, Lilley AK, Timms-Wilson TM, Spencer-Phillips PTN, editors. Microbial ecology of aerial plant surfaces. Oxford (UK): CABI. p. 165–179.

Mandelbaum R, Hadar Y. 1997. Methods for determining *Pythium* suppression in container media. Compost Sci. Utilization. 5:15–22.

Maronek DM, Studebaker D, Oberly B. 1985. Improving media aeration in liner and container production. Comb. Proc. Intl. Plant Prop. Soc. 35:591–597.

Medina E, Paredes C, Pérez-Murcia MD, Bustamante MA, Moral R. 2009. Spent mushroom substrates as component of growing media for germination and growth of horticultural plants. Bioresour. Technol. 100:4227–4232.

Merrill R, McKeon J. 2001. Apparatus design and experimental protocol for organic compost teas. Organic Farm Res. Found. Inform. Bull. 9:9–15.

Michel FC, Marsh TJ, Reddy CA. 2002. Bacterial community structure during yard trimmings composting. In: Insam H, Riddech N, Klammer, editors. Microbiology of composting. Berlin (Germany): Springer-Verlag. p. 25–42.

Miller FC. 1992. Composting as a process based on the control of ecologically selective factors. In: Metting FBJr, editor. Soil microbial ecology: Applications in agricultural and environmental management. New York (NY): Marcel Dekker. p. 515–544.

Moustafa AM, Hoitink HAJ, Herr LJ, Schmitthenner AF. 1977. Suppression of damping-off of tomato in hardwood bark compost. Proc. Am. Phytopathol. Soc. 4:173.

Nakasaki K, Hiraoka S, Nagata H. 1998. A new operation for producing disease-suppressive compost from grass clippings. Appl. Environ. Microbiol. 64:4015–4020.

National Organic Standards Board. 2011. Compost tea task force report. Washington (DC): Author.

Nelson EB, Kuter GA, Hoitink HA. 1983. Effects of fungal antagonists and compost age on suppression of *Rhizoctonia* damping-off in container media amended with composted hardwood bark. Phytopathol. 73:1457–1462.

Noble R, Coventry E. 2005. Suppression of soil-borne plant diseases with composts: A review. Biocontrol Sci. Technol. 15:3–20.

Ntougias S, Papadopoulou KK, Zervakis GI, Kavroulakis N, Ehaliotis C. 2008. Suppression of soil-borne pathogens of tomato by composts derived from agro-industrial wastes abundant in Mediterranean regions. Biol. Fert. Soil. 44:1081–1090.

Ostos JC, López-Garrido R, Murillo JM, López R. 2008. Substitution of peat for municipal solid waste-and sewage sludge-based composts in nursery growing media: Effects on growth and nutrition of the native shrub *Pistacia lentiscus* L. Bioresour. Technol. 99:1793–1800.

Ownley BH, Benson DM. 1991. Relationship of matric water potential and air-filled porosity of container media to development of *Phytophthora* root rot of Rhododendron. Phytopathol. 81:936–941.

Pane C, Spaccini R, Piccolo A, Scala F, Bonanomi G. 2011. Compost amendments enhance peat suppressiveness to *Pythium ultimum, Rhizoctonia solani* and *Sclerotinia minor*. Biol. Control. 56:115–124.

Pascual I, Azcona I, Aguirreolea J, Morales F, Corpas FJ, Palma JM, Rellán-Álvarez R, Sánchez-Díaz M. 2010. Growth, yield, and fruit quality of pepper plants amended with two sanitized sewage sludges. J. Agric. Food Chem. 58:6951–6959.

Pascual J, Garcia C, Hernandez T, Lerma S, Lynch J. 2002. Effectiveness of municipal waste compost and its humic fraction in suppressing *Pythium ultimum*. Microbial Ecol. 44:59–68.

Paulin B, O'Malley P. 2008. Compost production and use in horticulture. Bull. No. 4746. Perth (Australia): Department of Agriculture and Food, Government of Western Australia.

Paulsrud B, Wien A, Nedland KT. 2000. A survey of toxic organics in Norwegian sewage sludge, compost and manure. Oslo (Norway): Aquateam, Norwegian Water Technology Centre.

Perez-Murcia MD, Moral R, Moreno-Caselles J, Perez-Espinosa A, Paredes C. 2006. Use of composted sewage sludge in growth media for broccoli. Bioresour. Technol. 97:123–130.

Persad R. 2000. Agricultural science for the Caribbean. Book 2. Cheltenham (UK): Nelson Thornes Ltd.

Pharand B, Carisse O, Benhamou N. 2002. Cytological aspects of compost-mediated induced resistance against *Fusarium* crown and root rot in tomato. Phytopathol. 92:424–438.

Pooyeh F, Peyvast G, Olfati JA. 2012. Growing media including palm waste in soilless culture of cucumber. Int. J. Veg. Sci. 18:20–28.

Ribeiro HM, Romero AM, Pereira H, Borges P, Cabral F, Vasconcelos E. 2007. Evaluation of a compost obtained from forestry wastes and solid phase of pig slurry as a substrate for seedlings production. Bioresour. Technol. 98:3294–3297.

Roberts DP, Lumsden RD. 1990. Effect of extracellular metabolites from *Gliocladium virens* on germination of sporangia and mycelial growth of *Pythium ultimum*. Phytopathol. 80:461–465.

Robertson RA. 1993. Peat, horticulture and environment. Biodivers. Conserv. 2:541–547.

Roe NE. 2000. Compost utilization in horticultural cropping systems. In: Stoffella PJ, Kahn BA, editors. Compost utilization in horticultural cropping systems. Boca Raton (FL): Lewis Publishers.

Roe NE, Kostewicz SR. 1992. Germination and early growth of vegetable seed in composts. Univ. Florida Proc. 101:191–201.

Ryckeboer J. 2001. Biowaste and yard waste composts: Microbiological and hygienic aspects-suppressiveness to plant diseases [PhD thesis]. Leuven (Belgium): Katholieke Universiteit Leuven.

Rynk R. 1992. On-farm composting handbook (NRAES-54). Ithaca (NY): Northeast Regional Agricutural Engineering Service.

Sánchez-Monedero MA, Roig A, Cegarra J, Bemal MP, Noguera P, Abad M, Anton A. 2004. Composts as media constituents for vegetable transplant production. Compost Sci. Util. 12:161–168.

Sang MK, Kim JG, Kim KD. 2010. Biocontrol activity and induction of systemic resistance in pepper by compost water extracts against *Phytophthora capsici*. Phytopathol. 100:774–783.

Santos M, Diánez F, Carretero F. 2011. Suppressive effects of compost tea on phytopathogens. In: Dubey NK, editor. Natural Products in Plant Pest Management. Oxford (UK): CABI Publishing. p. 242–262.

Sawhney BL. 1976. Leaf compost for container-grown plants. HortSci. 11:34–35.

Scheuerell SJ, Mahaffee WF. 2002. Compost tea: Principles and prospects for plant disease control. Compost Sci. Util. 10:313–338.

Scheuerell SJ, Mahaffee WF. 2004. Compost tea as a container medium drench for suppressing seedling damping-off caused by *Pythium ultimum*. Phytopathol. 94:1156–1163.

Scheuerell SJ, Mahaffee WF. 2006. Variability associated with suppression of gray mold (*Botrytis cinerea*) on geranium by foliar applications of nonaerated and aerated compost teas. Plant Dis. 90:1201–1208.

Schroeder FG, Sell H. 2007. Use of compost made from livestock manure as an organic substrate for cucumber (*Cucumis sativus* L.) grown in greenhouse. Acta Hort. (ISHS). 819:367–372.

Siddiqui Y, Meon S, Ismail R, Rahmani M. 2009. Bio-potential of compost tea from agro-waste to suppress *Choanephora cucurbitarum* L. the causal pathogen of wet rot of okra. Biol. Control. 49:38–44.

Siddiqui Y, Meon S, Ismail R, Rahmani M, Ali A. 2008. Bio-efficiency of compost extracts on the wet rot incidence, morphological and physiological growth of okra (*Abelmoschus esculentus* [(L.) Moench]). Sci. Hortic. 117:9–14.

Sivan A, Chet I. 1989. The possible pole of competition between *Trichoderma harxianum* and *Fusarium oxysporum* on rhizosphere colonization. Phytopathol. 79:198–203.

SoilSoup. 2012. Products: Brewing equipment. Microbial magic [Internet]. SoilSoup; [cited 2012 Feb 27]. Available from: http://www.soilsoup.com/soil-soup-brewing-equipment.html

Spiers TM, Fietje G. 2000. Green waste compost as a component in soilless growing media. Compost Sci. Util. 8:19–23.

Spring DE, Ellis MA, Spotts RA, Hoitink HAJ, Schmitthenner AF. 1980. Suppression of the apple collar rot pathogen in composted hardwood bark. Phytopathol. 70:1209–1212.

Srivastava R, Khalid A, Singh US, Sharma AK. 2010. Evaluation of arbuscular mycorrhizal fungus, fluorescent *Pseudomonas* and *Trichoderma harzianum* formulation against *Fusarium oxysporum* f. sp. *lycopersici* for the management of tomato wilt. Biol. Control. 53:24–31.

Sterrett SB, Chaney RL. 1982. Growth of vegetable transplants and bedding plants in sewage sludge compost media. HortSci. 17:479, (Abstract).

Stoffella PJ, Graetz DA. 1996. Sugarcane filtercake compost influence on tomato emergence, seedling growth, and yields. In: Bertoldi MD, Sequi P, Lemmes B, Papi T, editors. The science of composting: Part 2. Glasgow (UK): Blackie Academic and Professional. p. 1351–1356.

Stoffella PJ, Kahn BA. 2001. Compost utilization in horticultural cropping systems. Boca Raton (FL): CRC Press.

Suarez-Estrella F, Vargas-Garcia C, Lopez MJ, Capel C, Moreno J. 2007. Antagonistic activity of bacteria and fungi from horticultural compost against *Fusarium oxysporum* f. sp. *melonis*. Crop Prot. 26:46–53.

Sullivan DM, Miller RO. 2000. Compost, quality attributes, measurements and variability. In: Stoffella PJ, Kahn BA, editors. Compost utilization in horticultural cropping systems. Boca Raton (FL): CRC Press. p. 95–120.

Sustainable Agricultural Technologies, Inc. 2012. Earth tea brewers [Internet]. Sustainable Agricultural Technologies, Inc; [cited 2012 Feb 27]. Available from: http://www.composttea.com/earth_tea_brewers1.htm.

Termorshuizen AJ, Van Rijn E, Van Der Gaag DJ, Alabouvette C, Chen Y, Lagerlöf J, Malandrakis AA, Paplomatas EJ, Rämert B, Ryckeboer J. 2006. Suppressiveness of 18 composts against 7 pathosystems: Variability in pathogen response. Soil Biol. Biochem. 38:2461–2477.

Tränkner A. 1992. Use of agricultural and municipal organic wastes to develop suppressiveness to plant pathogens. In: Tjamos ES, Papavizas GC, Cook RJ, editors. Biological control of plant diseases. New York (NY): Plenum Press. p. 35–42.

Trillas MI, Casanova E, Cotxarrera L, Ordovás J, Borrero C, Avilqs M. 2006. Composts from agricultural waste and the *Trichoderma asperellum* strain T-34 suppress *Rhizoctonia solani* in cucumber seedlings. Biol. Control. 39:32–38.

Tuitert G, Szczech M, Bollen GJ. 1998. Suppression of *Rhizoctonia solani* in potting mixtures amended with compost made from organic household waste. Phytopathol. 88:764–773.

Van Beneden S, Roobroeck D, Franta SC, De Neve S, Boeckx P, Höfte M. 2010. Microbial populations involved in the suppression of *Rhizoctonia solani* AG1-1B by lignin incorporation in soil. Soil Biol. Biochem. 42:1268–1274.

Vavrina CS. 1994. Municipal solid waste materials as soilless media for tomato transplant production. Proc. Florida State Hort. Soc. 107:118–120.

Vavrina CS, Ozores-Hampton M, Armbrester K, Pena M. 1996. Spent mushroom compost and biological amendments as an alternative to soilless media. Southwest Florida Research and Education Center Report-Veg. 96.3. Immokalee, FL: University of Florida.

Walker P, Williams D, Waliczek TM. 2006. An analysis of the horticulture industry as a potential value-added market for compost. Compost Sci. Util. 14:23–31.

Weimer K, Kern M. 1989. Kompostierung International [Compost International]. Abfall Wirtschaft [Technical Series] No. 2. Witzenhausen (Germany): University of Kassel MIC Baeza Verlag. p. 400.

Weimer K, Kern M. 1992. Gütesicherung und Vermarktung von Bioabfallkompost. [Quality Cerification and Marketing of Compost] Technical Series 9. Witzenhausen (Germany): University of Kassel MIC Baeza Verlag. p. 710.
Weltzien HC. 1990. The use of composted materials for leaf disease suppression in field crops. Monogr. Br. Crop Prot. Counc. 45:115–120.
Weltzien HC. 1991. Biocontrol of foliar fungal diseases with compost extracts. In: Andrews JH, Hirano SS, editors. Microbial ecology of leaves. New York (NY): Springer. p. 430–450.
Woo SL, Scala F, Ruocco M, Lorito M. 2006. The molecular biology of the interactions between *Trichoderma* spp., phytopathogenic fungi, and plants. Phytopathol. 96:181–185.
Xu D, Raza W, Yu G, Zhao Q, Shen Q, Huang Q. 2012. Phytotoxicity analysis of extracts from compost and their ability to inhibit soil-borne pathogenic fungi and reduce root-knot nematodes. World J. Microbiol. Biotechnol. 28:1193–1201.
Yeager T et al. 2007. Best management practices: Guide for producing nursery crops. Atlanta (GA): The Southern Nursery Association.
Yohalem DS, Harris RF, Andrews JH. 1994. Aqueous extracts of spent mushroom substrate for foliar disease control. Compost Sci. Util. 2:67–74.
Yohalem DS, Voland R, Nordheim EV, Harris RF, Andrews JH. 1996. Sample size requirements to evaluate spore germination inhibition by compost extracts. Soil Biol. Biochem. 28:519–525.
Zapata N, Guerrero F, Polo A. 2005. Evaluation of pine bark and urban wastes as components of plant growth media. Agric. Téc. 65:378–387.
Zhang W, Dick WA, Hoitink HAJ. 1996. Compost-induced systemic acquired resistance in cucumber to *Pythium* root rot and anthracnose. Phytopathol. 86:1066–1070.
Zmora-Nahum S, Danon M, Hadar Y, Chen Y. 2008. Chemical properties of compost extracts inhibitory to germination of *Sclerotium rolfsii*. Soil Biol. Biochem. 40:2523–2529.