Compost Tea: Principles and Prospects For Plant Disease Control

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LITERATURE REVIEW

Compost Tea: Principles and Prospects For Plant Disease Control

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An increasing body of experimental evidence indicates that plant disease can be suppressed by treating plant surfaces with a variety of water-based compost preparations, referred to in the literature as watery fermented compost extracts or compost teas. The terms nonaerated compost teas (NCT) and aerated compost teas (ACT) are used in this review to refer to the common production methods that diverge in the intent to actively aerate. Very little data directly compares the efficacy of NCT and ACT for plant disease suppression. A variety of foliar plant pathogens and/or diseases have been suppressed by applications of NCT while few controlled studies have examined ACT. For some diseases the level of control would be considered inadequate for conventional agriculture; organic producers with limited control options consider partial disease control to be an important improvement. For both compost tea production methods, decisions that influence pathogen suppression include choice of compost feedstocks, compost age, water ratio, fermentation time, added nutrients, temperature and pH. Application technology choices include the dilution ratio, application equipment, timing, rates, spray adjuncts and adding specific microbial antagonists. Increased understanding of compost tea microbiology and the survival and interactions of microbes on plants surfaces should make it possible to modify compost tea production practices and application technology to optimize delivery of a microflora with multiple modes of pathogen suppression. Innovative growers and practitioners are leading the development of new compost tea production methods and uses, generating many potential research opportunities. The use of compost tea as part of an integrated plant health management strategy will require much additional whole systems research by a cohesive team of farmers and experts in composting, plant pathology, phyllosphere biology, molecular microbial ecology, fermentation science, plant physiology, plant breeding, soil science, and horticulture.

Introduction

Soil and plant sprays based on compost and various plant materials have been in practice since the 1920s (Koepf 1992). Applying compost in liquid form has roots in an old gardening practice of soaking seeds and drenching plants or soil with 'compost water' for fertilization and to help prevent damping-off (Rodale 1967). An increasing body of experimental evidence indicates that plant disease can be suppressed by applying a variety of water-based compost preparations (reviewed in Weltzien (1991) and Diver (1998)). There has been a recent surge of popular interest in the potential for improving plant health through the use of water-based compost sprays, typically called compost teas.

There are several reasons why compost tea use is expanding (Touart 2000; Scheuerell, personal observation). Garden writers are exposing the idea to a wide audience. Professional landscapers are using compost tea and educating clients. Golf courses are assessing compost tea for fertility and disease control. Municipal parks and recreation departments are using compost tea for grounds maintenance. A number of individuals and companies are selling compost tea at farmers markets, retail outlets, internet sites, and through application services.

Major reasons why organic farmers are experimenting with compost tea include the lack of approved disease management tools and their utility for integration into existing plant fertility and microbial inoculation programs. As the number of growers using compost tea expands, so has the number of unconfirmed reports of foliar plant disease control. Several examples include *Botrytis* on green beans, strawberries, grapes, and geranium; powdery mildew on apples; black spot and powdery mildew on roses; late blight on greenhouse tomatoes; and downy mildew on *Brassica* seedlings. Testimonials attributing compost tea to soil borne disease control include reduced damping-off of direct sown crops by drenching the seed row and drenching transplanted seedling plugs. Dipping potato seed pieces and ornamental flower bulbs is thought to reduce root rots and is commercially practiced. At least one greenhouse grower has observed reduced fusarium root rot of cyclamen through the use of compost tea drenches.

Despite growers' concerns over the lack of information available to guide on-farm trials with compost tea, they continue to experiment with compost tea due to the lack of available control measures. Anecdotal success stories abound, but many lack good experimental design, objective assessment strategies or supportive data. In spite of this, many practitioners have continued to expand their capacity to make and use compost tea. This is strong evidence that measurable benefits are being perceived and that a better understanding of compost tea and its uses is needed.

Innovative growers and practitioners are leading the development of new compost tea production methods and uses, generating many potential research opportunities. The purpose of this review is to summarize much of the current knowledge of plant disease suppression with compost tea and indicate future directions. It is particularly important to properly attribute the role of aeration in documented cases of disease suppression, as there appears to be confusion in recent publications (Ingham and Alms 1999; Merril and McKeon 2001). In addition, disease suppression has been attributed to compost tea when the cited literature describes the incorporation of solid compost (Merril and McKeon 2001; Quarles 2001). It should become clear that our understanding of compost tea is in its infancy and more research is needed. This review aims to help establish a common knowledge base to facilitate communication and collaboration between practitioners and researchers.

Terminology

During the 1990s, water-based compost preparations received increasing attention from growers and researchers resulting in a proliferation of preparation methodologies and terminologies (Brinton 1995; Diver 2001). Numerous terms have been used to describe compost fermentations — compost tea, aerated compost tea, organic tea, compost extracts, watery fermented compost extract, amended extracts, steepages, and slurries — and each needs to be clarified. Many are synonymous with each other or are easily confused with other concepts.

'Compost tea' has been described as the product of showering recirculated water through a porous bag of compost suspended over an open tank with the intent of maintaining aerobic conditions (Riggle 1996). The product of this method has also been termed 'aerated compost tea' (Pscheidt and Wittig 1996) and 'organic tea' (Merrill and McKeon 2001). Several companies have developed various units for making compost tea under highly aerated conditions. Each company describes the end product as 'compost tea' thus effectively cementing the term 'compost tea' into common usage.

The use of the term 'compost extract' poses a particular challenge due to the widespread use of this term in studies on the chemical properties of compost

(Krogstadt and Solbraa 1975; Chanyasak and Kubota 1981); in studies examining the *in vitro* inhibition of soil fungal pathogens by organic materials (Sivasithamparam 1981; Kai *et al.* 1990; Hardy and Sivasithamparam 1991); and in the *in vitro* immobilization of nematodes by toxic compounds extracted from composted municipal refuse (Hunt 1973). These studies use 'extract' to indicate that the samples were obtained by pressure, distillation, evaporation or treatment with a solvent (Cayne 1989). The term 'compost extract' should be reserved for describing the filtered product of compost mixed with any solvent, but not fermented, when used for analytical or assay work.

Compost extracts, watery fermented compost extracts, amended extracts, compost steepages, compost slurry, and compost tea have been used to refer to nonaerated fermentations. 'Compost extract' (Weltzien 1989), 'watery fermented compost extracts'(Weltzien 1991) and 'steepages' (Hoitink *et al.* 1997) are synonyms, defined as a 1:5 to 1:10 (v:v) ratio of compost to water that is fermented without stirring at room temperature in an open container for a defined length of time. 'Amended extracts' are compost extracts that have been fermented with the addition of specific nutrients or combined with isolated microorganisms before application (Welztien 1991). 'Compost slurry' has been used to describe nonaerated compost teas prior to filtration (Cronin *et al.* 1996). Brinton (*et al.* 1996) defines compost extracts or teas as a "deliberate production of specific (water) extracts based on composts of known properties and age" without distinguishing between nonaerated and aerated production.

Since the term 'compost tea' has not always been uniformly associated with an aerated fermentation process (Brinton *et al. 1996*; Quarles 2001; Sideman 1996;Yohalem 1996a) further clarification is needed. It is tempting to use aerobic or anaerobic prefixes to label compost tea. However, without actually measuring oxygen concentrations, it is unclear how to define the aerobic, microaerobic, and anaerobic gradients of oxygen found in open fermentation vessels (Johnson,1999). For clarity, we will use the terms nonaerated compost teas (NCT) and aerated compost teas (ACT) throughout this review to refer to the two dominant compost fermentation methods. ACT will refer to any method in which water is actively aerated during the fermentation process. NCT will refer to methods that do not disturb or only minimally disturb the fermentation after initial mixing. The term compost tea is retained because of the ubiquitous use of the term among practitioners.

Methods for Producing Compost Teas

Two dominant approaches being advocated in compost tea production are aerated and nonaerated methods. Irrespective of aeration, both methods intentionally ferment well-characterized compost in water for a defined period of time. Throughout this review fermentation is used in the common way, meaning the cultivation of microorganisms (Hilton 1999). Both methods of compost tea production (Table 1) require a fermentation vessel, compost, water, incubation, and filtration. Nutrients may be added before or after fermentation and various spray adjuvants can be added prior to application of undiluted or diluted tea.

There is debate over the necessity to aerate during compost tea production (Brinton *et al.* 1996; Ingham 1999 and 2000b). Aerated production methods are associated with reduced production time. Nonaerated production is associated with low cost, low energy input and many documented reports of plant disease control (Weltzien 1991). NCT production has been suggested to cause phytotoxicity and provide an optimal environment for human pathogen regrowth. However, we are not aware of any doc-

TABLE 1
Process Steps for production of compost teas

Process Step	Nonaerated (NCT)	NCT issue	Aerated (ACT)	ACT Issue	Common Issue
Fermentation vessel	Open container	Inexpensive Reliable	Make or buy	Expense and reliability	Free of biocide residues
Compost source	Mixed with water in the vessel		Typically held in perforated container within the vessel		Pathogen free. Feedstocks and age affect suppression
Water source and ratio	1:4 to 1:10 compost:water ratio		Ratios of 1:10 to 1:50 in commercial units		Dechlorinated
Fermentation nutrients		Foul odor issue		Some nutrients foam excessively eg saponin. Need defoamers	Can increase microbes, disease control, also pathogens
Fermentation duration	Range from 1-21 days	Optimum must be determined experimentally	Range from 18 hours to weeks, depending on technology	Fast times may may have residual nutrients that stimulate pathogens	Longer times prevent timing flexibility
Filtration			Integrated in some commercial units		Nozzle or emitter dependent
Dilute for use		Most work done with undiluted NCT		Proposed guidelines, see text	Depends on intended use and experience
Tank mix Nutrients Surfactants Stickers UV stabilizers					Can improve disease control, nutrients may increase pathogens
Spray equipment					PSI, velocity, sheer, pressure drop effects
Spray timing rate					Use preventively, total coverage needed

umented evidence to substantiate this claim, nor have we observed phytotoxic symptoms when NCT was used as a foliar spray or potting mix drench (Scheuerell and Mahaffee, unpublished data). There are no biological grounds to substantiate the claim that low oxygen conditions are ideal for most human pathogens to grow (Murray 1999). Well-designed experiments that directly compare both production methods are necessary to determine the utility of aeration.

Aerated production requires mechanics and energy for continuous air addition; a number of designs are currently in use. Common aeration designs include showering recirculated water through a porous bag of compost that is suspended over an open tank (Cantisano 1995; Riggle 1996; Merril 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.com), venturi nozzles (Composttea.com), aquarium stones (Ingham 2000a), or fine bubble diffusion mats (Growingsolutions.com, Compara.com). There are a growing number of companies offering units that produce aerobic 'compost tea' by suspending compost in a fermentation vessel and actively aerating and/or recirculating the liquid (Diver 2001).

NCT has traditionally been made by mixing one volume compost with four to ten volumes of water in an open container, initially stirring the mixture, and then leaving it undisturbed at 15-25°C for at least three days (Weltzien 1991). Brinton (*et al.* 1996) advocates stirring NCT every two to three days during the fermentation to possibly facilitate the release of microbes from compost particles. Container sizes range from several thousand liters down to small buckets. However, to avoid compost sampling error, at least 500g compost should be used when considering experimental designs for *in vitro* inhibition screening with NCT (Yohalem *et al.* 1996b).

Other preparation methods are in limited practice and have not been assessed in controlled studies for disease suppression. One method involves straining water through compost-filled sacks directly into a spray tank for use (Diver 1998). Another method is to make instant compost tea by mixing water with finely ground compost without fermentation or filtration before use (Don Cranford, personal communication). Gardening lore also recommends hanging burlap bags filled with compost in water barrels to produce a plant drench (Peavy 1992). Several other related preparations have been made including herbal or manure teas (Diver 2001), but will not be discussed further. Regardless of preparation method, compost teas are typically applied with conventional pesticide spray equipment after filtering out material that would clog the nozzles (Brinton *et al.* 1996, Ingham 2000b).

For clarity, research reports on the use of compost tea should include detailed information on several fermentation and application parameters (Table 2). As a group, the fermentation parameters will influence the composition and population of microbial species in the final product. The application parameters influence the extent of target coverage and establishment of the applied microorganisms on plant surfaces.

TABLE 2.
Fermentation and application parameters that could influence compost tea production and efficacy.

	Fermentation Parameters
Fermentation vessel	Dimensions, manufacturer and model if applicable
Compost	Producer, feedstocks, age, stability, % moisture, available nutrients, microbial analysis, either volume and bulk density used or weight
Water source	Volume, initial and final temperature
Fermentation nutrients	Source, quantity and timing
Oxygen content in ppm	Include any stirring, agitation, or aeration; indicate time of reading(s) during production
Fermentation duration	Method of storage if not used immediately
	Application Parameters
Filtration	Material used for filtering
Dilution ratio	Water source used
Adjuncts	Nutrients, surfactants, stickers, UV stabilizers, microorganisms
Application equipment	Make, model, nozzle specifications, PSI
Application	Rate, time of day, weather, interval between applications

Effect on Plant Disease

Very little data directly compares nonaerated and aerated production methodologies for plant disease control. Cronin *et al.* (1996) used a manure-based spent mush-

TABLE 3.
Summary of experiments using nonaerated compost tea (NCT) for plant disease control.

Pathogen	Host Tissue	Scale[1]	Control[2]	Pathogen Inoculated	Compost Type	Optimum Fermention Duration	Fermenation Nutrients	Spray Adjuncts	Source
Alternaria panax	Ginseng	IV SA	– –	5×10^5 spores/ml	Spent mushroom	7 days	None	None	Yohalem *et al* 1994
Alternaria solani	Tomato plants	Field	+	Conidia, amount not stated	Cattle manure	14 days	None	None	Tsror, 1999
Botrytis cinerea	Bean	IV DL	+ +	2×10^6 spores/ml	Horse bedding, chicken litter	8 days	None	None	McQuilken *et al.* 1994
Botrytis cinerea	Bean	DL	+	2×10^6 spores/ml	Cattle manure	24 hours	0.5-1.0% yeast extract	None	Urban and Trankner 1993
Botrytis cinerea	Bean	DL	+	2×10^6 spores/ml	Horse manure	24 hours	0.5-1.0% yeast extract	None	Urban and Trankner 1993
Botrytis cinerea	Grape	DL berries	+	2×10^6 spores/ml	Horse-straw-soil	8 days	None	None	Ketterer *et al.* 1992
Botrytis cinerea	Grape berries	Field	+ +	2×10^6 spores/ml	Horse-straw-soil	2 and 4 months	0.5 % casein + 0.05 pine oil	None	Ketterer *et al.* 1992
Botrytis cinerea	Lettuce	GH	+	2×10^6 spores/ml	Horse bedding, chicken litter	8 days	None	None	McQuilken *et al.* 1994
Botrytis cinerea	Strawberry	Field	-	Natural	Cattle manure	7-21 days	None	None	Welke 1999
Botrytis cinerea	Strawberry	Field	-	Natural	Chicken manure	7-21 days	None	None	Welke 1999
Botrytis cinerea	Strawberry	Field	+	Natural	Cattle manure	16 days	None	None	Stindt 1990
Botrytis cinerea	Strawberry	Field	+	Natural	Horse manure	12 weeks	None	None	Stindt 1990
Botrytis cinerea	Strawberry	Field	+ early - late season	2×10^6 spores/ml	Horse-straw-soil	24 hours	1.0% yeast extract	None	Urban and Trankner 1993
Botrytis cinerea	Tomato Pepper Grape	DL DL berries	+ + +	2×10^5 spores/ml	Cattle manure	14 days	Nutrient broth didn't increase suppression of 10 day fermentations	None	Elad and Shtienberg 1994
Botrytis cinerea	Tomato Pepper Grape	DL DL berries	+ + +	2×10^5 spores/ml	Horse manure	14 days	Nutrient broth didn't increase suppression of 10 day fermentations	None	Elad and Shtienberg 1994
Botrytis cinerea	Tomato Pepper Grape	DL DL berries	- + +	2×10^5 spores/ml	Grape marc	14 days	Nutrient broth didn't increase suppression of 10 day fermentations	None	Elad and Shtienberg 1994
Botrytis cinerea	Tomato foliage	GH	+	Natural	Cattle manure	14 day	None	None	Elad and Shtienberg 1994
Cochliobolus carbonum	Maize	IV SA	+ +	5×10^5 spores/ml	Spent mushroom	7 days	None	None	Yohalem *et al.* 1994
Erysiphe polygoni	Bean	GH	+	Not stated	Not stated	7-14 days	None	0.5% casein	Ketterer and Schwager, 1992
Phytophthora infestans	Potato	Field Field	- +	Natural	Horse-straw-soil	7 day	controlled only by adding pure cultures of microbial antagonists to tea just before spraying		Ketterer 1990
Phytophthora infestans	Potato	SA Field	+ -	?	?	?	None	None	Jongebloed *et al.* 1993

continued

TABLE 3. continued

Pathogen	Host Tissue	Scale[1]	Control[2]	Pathogen Inoculated	Compost Type	Optimum Fermention Duration	Fermenation Nutrients	Spray Adjuncts	Source
Phytophthora infestans	Tomato	GH	+	Not stated	Not stated	7-14 days	None	0.5% casein	Ketterer and Schwager, 1992
Phytophthora infestans	Tomato	DL	+	8×10^4 sporangia/ml	Horse-straw-soil	14 day	None	None	Ketterer 1990
Plasmopara viticola	Grape	DL	+	8×10^4 sporangia/ml	Horse-straw-soil	3 days	None	None	Weltzien and Ketterer 1986a
Plasmopara viticola	Grape	Field	+	Natural	Horse-straw-soil	3 days	adding pure cultures of microbial antagonists just before spraying significantly increased control		Ketterer 1990
Plasmopora viticola	Grape	DL GH	+ +	1×10^4 sporangia/ml	Fresh cow dung, soil	14 days	None	None	Achimu and Schlosser 1992
Pseudopeziza tracheiphila	Grape	Field	+	ND	Horse-straw-soil	3 days	None	None	Weltzien 1989
Psuedomonas syringae	Arabidopsis	SA	+	1×10^8 cfu/ml	Pine bark	7 days	None	None	Zhang *et al.* 1998
Sphaeropsis sapinea	Red pine	IV SA	+ +	5×10^5 spores/ml	Spent mushroom	7 days	None	None	Yohalem *et al.* 1994
Sphaerotheca fuliginea	Cucumber	DL	+	Yes, ND	Carious	Various	None	None	Samerski and Weltzien 1988
Sphaerotheca pannosa	Rose	Field	+	Natural	Chicken manure	7-11 days	0.3% molasses	None	Scheuerell and Mahaffee 2000b
Sphaerotheca pannosa	Rose	Field	+	Natural	Yard debris	7-11 days	0.3% molasses	None	Scheuerell and Mahaffee 2000b
Sphaerotheca pannosa	Rose	Field	+	Natural	Mixed source	7-11 days	0.3% molasses	None	Scheuerell and Mahaffee 2000b
Uncinula necator	Grape	GH	+	ND	Horse-straw-soil	3 days	None	None	Weltzien 1989
Uncinula necator	Grape	Field	+ +	Natural	Cattle manure	3 days	None	None	Sackenheim 1993
Uncinula necator	Grape	Field	+	Natural	Horse manure	3 days	None	None	Sackenheim 1993
Uncinula necator	Grape	Field	+	Natural	Horse manure	3 days	None	Caso bouillon, rape oil 0.5%	Sackenheim 1993
Venturia inaequalis	Apple	IV SA	+ +	5×10^5 spores/ml	Spent mushroom	7 days	None	None	Yohalem *et al.* 1994
Venturia inaequalis	Apple	Field	-	Natural	Spent mushroom	7 days	None	None	Andrews 1993
Venturia inaequalis	apple	Field	-	Natural	Cattle manure	7 days	None	None	Andrews 1993
Venturia inaequalis	Apple	Field	+	Natural	Spent mushroom	7 days	None	Latron B1956 0.06% or fish oil 0.025%	Yohalem *et al.* 1996
Venturia inaequalis	Apple	Field	+	Yes, ND	Manure-straw-soil	5-7 days	None	None	Trankner and Kirchner-Bierschenk 1988
Xanthomonas campestris	Tomato	SA Field	+ -	1×10^8 cfu/ml	Cow manure	7 days	None	None	Ai-Dahmani and Hoitink 1999

[1]Experimental scale: IV - in vitro, DL - detached leaf, SA - seedling assay, GH - commercial greenhouse setting, Field - outdoor agronomic conditions. [2] Control: + treatments statistically less disease than control treatment (minimum $p = 0.05$); - treatment no difference from control treatment

room compost to compare NCT and an air-bubbled ACT for *in vitro* effects on germination of conidia of *Venturia inaequalis*. They concluded that seven day NCT inhibited germination while the ACT had no effect. Conidial inhibition was induced after the seven day aerated fermentations were allowed to incubate for an additional seven days without aeration.

Scheuerell and Mahaffee (2000b) examined the role of aeration and three compost types (yard debris, chicken manure/sawdust, CMC mixed source) in producing compost teas for controlling powdery mildew (*Sphaerotheca pannosa* var. *rosae*) on field grown roses. The ACT were fermented for 24 hours in commercial compost tea 'brewers'. The NCT's were fermented in buckets for seven to ten days. Applications were made every seven to 11 days over a five month season. All six compost teas significantly reduced powdery mildew incidence on leaflets compared to a water spray control; within each compost type there was no difference between the ACT and NCT. The composted chicken manure produced the most suppressive compost teas. The authors concluded that compost source was more important than aeration for maximizing disease control.

A variety of foliar diseases have been suppressed by applications of NCT. A range of experimental approaches and scales have been utilized including *in vitro* inhibition, seedling assays, detached leaves, growth chambers, production greenhouses, and field studies (Table 3). The large number of studies supporting the use of NCT for pathogen suppression indicates that it is a viable tool. A number of these studies have been reviewed previously (Weltzien 1991).

Research on the use of ACT to control foliar and fruit diseases is summarized in Table 4. The limited number of controlled studies using ACT have not been widely circulated and therefore will be covered in more detail here. In the Willamette Valley Oregon, Pscheidt and Wittig (1996) did not observe significant control of powdery mildew of apple or grape, apple scab, pear scab, brown rot of peach, peach leaf curl, and cherry leaf spot when ACT was applied in the field on regular intervals. One significant result, reduced incidence of brown rot blossom blight (*Monilinia laxa*) on sweet cherry, was observed. The ACT was stored in containers for 12-15 hours overnight, and it is unknown if this could have negatively influenced the observed level of suppression for all host-pathogen combinations.

Other farm trials used ACT on a variety of crops with variable yield and disease control (Granatstein 1999). No effect of ACT applications on early blight of tomato was observed. Lettuce drop incidence was reduced in a summer but not a spring crop. Postharvest fruit rot of blueberries was significantly reduced, but offset by reduced yields. Spinach yield also decreased, but spring and summer broccoli yields increased. It is apparent that impacts on plant health and yield can be crop specific and general inferences about disease suppression or yield cannot be made.

While relatively little research has been conducted on soil-borne disease suppression with compost tea drenches, this technique is practiced in the organic agriculture community. NCT was investigated for use as a seed treatment to prevent pea seedling damping-off caused by *Pythium ultimum* (Tränkner 1992). NCT's prepared from either cattle manure or grape marc and fermented for five or ten days were effective in suppressing *in vitro Pythium* mycelial growth. They also significantly increased seed germination, root length, and root dry weight when seeds were soaked, redried, and sown two days later in soil inoculated with *P. ultimum*. Weltzien (1991) reports that *Rhizoctonia solani* has been suppressed *in vitro* by NCT and that heat sterilizing the NCT increased radial growth of Rhizoctonia colonies relative to an untreated control. Significant control of Fusarium wilt of pepper (*F. oxysporum* f. sp. *vasinfectum*) and cucumber (*F. oxysporum* f. sp. *cucumerinum*) by drenching NCT in greenhouse tests has recently

TABLE 4.
Summary of experiments using aerated compost tea (ACT) for plant disease control.

Pathogen	Host Tissue	Control[1]	Scale	Pathogen Inoculated	Compost Type	Fermention Duration	Fermenation Nutrients	Source
Alternaria + Septoria	Tomato foliage	-	Field	Natural	Vermi-compost	24 hours	Soil Soup solution[2]	Barker-Plotkin 2000
Alternaria alternata	Tomato foliage	-	Field	Natural	Not reported	24 hours	1.25% molasses, rock flour	Granatstein 1999
Blumeriella jaapii	Cherry leaves	-	Field	Natural	Not reported	24 hours rock dust	0.5% molasses	Pscheidt and Wittig 1996
Drop rot, pathogen lot reported	Lettuce	-spring +summer	Field	Natural	Not reported	24 hours	1.25% molasses, rock flour	Granatstein 1999
Monilinia fructicola	Peach fruit - postharvest	-	Field	Natural	Not reported	24 hours	0.5% molasses rock dust	Pscheidt and Wittig 1996
Monilinia taxa	Cherry blossom	+	Field	Natural	Not reported	24 hours rock dust	0.5% molasses	Pscheidt and Wittig 1996
Podosphaera leucotricha	Apple terminals	-	Field	Natural	Not reported	24 hours	0.5% molasses rock dust	Pscheidt and Wittig 1996
Post harvest loss	Blueberry fruit	+	Field	Natural	Not reported	24 hours	1.25% molasses, rock flour	Granatstein 1999
Sphaerotheca pannosa	Rose	+	Field	Natural	Chicken manure	24 hours	0.3% molasses	Scheuerell and Mahaffee 2000b
Sphaerotheca pannosa	Rose	+	Field	Natural	Mixed source	24 hours	0.3% molasses	Scheuerell and Mahaffee 2000b
Sphaerotheca pannosa	Rose	+	Field	Natural	Yard debris	24 hours	0.3% molasses	Scheuerell and Mahaffee 2000b
Taphrina deformans	Peach leaves	-	Field	Natural	Not reported	24 hours	0.5% molasses rock dust	Pscheidt and Wittig 1996
Uncinula necator	Grape - leaves -clusters	- +	Field	Natural	Not reported	24 hours	0.5% molasses rock dust	Pscheidt and Wittig 1996
Venturia inaequalis	Apple - leaves - fruit	- -	Field	Natural	Not reported	24 hours	0.5% molasses rock dust	Pscheidt and Wittig 1996
Venturia inaequalis	Conidia germination	-	In vitro		Spent mushroom	Bubbled for 7 days	None	Cronin *et al.* 1996
Venturia pirina	Pear fruit	-	Field	Natural	Not reported	24 hours	0.5% molasses rock dust	Pscheidt and Wittig 1996

[1] Control: + treatments statistically less disease than control treatment (minimum p = 0.05); - treatment no difference from control treatment; [2] Commercial product containing molasses, kelp, bat guano, citric acid, $MgSO_4$ (Soil Soup Inc., Edmonds, WA)

been reported (Ma *et al.* 1999; Ma *et al.* 2001). The NCT had an *in vitro* mycolytic effect on *Fusarium* microspores and chlamydospores, indicating that destruction of pathogen propagules could be playing a role in disease suppression. The potential of using compost tea for controlling soil borne disease, especially as a potted plant drench, deserves further research.

There is increasing interest among ACT practitioners to have their product tested by commercial laboratories for *in vitro* suppression of various soil-borne pathogens; some growers have reportedly used these assays to select for improvements in the suppressive qualities of their compost tea (Vicki Bess, BBC laboratories, personal communication). However, it is well established that *in vitro* inhibition is not always a good predictor of disease suppression when used as a screen for microbial antagonists (Cook and Baker 1983). For compost tea, assessing the utility of *in vitro* pathogen screening will require data correlating *in vitro* results to suppression under field conditions. Testing compost tea 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. However, all assays suffer from the complication that the tested batch of compost tea is ready for use well before assay results are available. Testing multiple batches over time could establish a probability that the same effect would be observed from a particular tea production process, but this requires significant time and cost for each pathogen.

Mode of Action

Multiple modes of activity are involved in suppressing plant disease with NCT; yet to date no studies have determined the mechanisms involved with ACT. Induced resistance, antibiosis, and competition have been used to explain suppression of foliar pathogens by NCT. Besides the report of *Fusarium* spore lysis (Ma *et al.* 2001), direct destruction of pathogen structures has not been reported with compost tea whereas this observation has been made for control of root rot pathogens with compost (Hadar and Gorodecki 1991). Considering the diverse microbial community in compost tea, it is likely that multiple modes of activity associated with microbial antagonists are involved in disease suppression.

Compost teas can induce plant defense responses. *In vitro* germination of *Sphaerotheca fuliginea* conidia was not inhibited by NCT, yet treated cucumber leaves responded to infecting conidia by increased papillae formation, lignification and necrotic reactions compared to nontreated leaves (Samerski and Weltzien 1988). These observations indicate that host responses to the pathogen were altered. Similary, Zhang and coworkers (1998) used beta-1,3-glucuronidase (GUS) activity as a marker of plant defense gene induction when studying Arabidopsis bacterial speck caused by *Pseudomonas syringae* pv. *maculicola*. GUS activity was induced equally in Arabidopsis plants by topical sprays of a composted pine bark NCT or salycylic acid. These results indicate that application of compost teas can stimulate plant defense reactions.

Several studies have determined that antibiosis is a mechanism of suppression based on observations that filter or heat sterilized NCT retain suppressive qualities (Elad and Shtienberg 1994, Yohalem *et al.* 1994, Cronin *et al.* 1996). Cronin *et al.* (1996) elucidated that antibiosis was the mechanism of inhibiting *in vitro* conidia germination of *Venturia inaequalis* by spent mushroom NCT. When the compost was sterilized and then fermented, no suppressive activity was found. However, fermenting nonsterilized compost produced NCT that had equally suppressive activity after 0.1*um* filtration, and it maintained most of the suppressive activity after autoclaving. Using microconcentrators, the major inhibitory agent was determined to be a low molecular weight (<3 kDa), heat stable, nonprotein metabolite produced by microorganisms during NCT fermentation.

There is evidence that some antibiotic metabolites present in compost tea originate from the compost source. Al-Dahmani *et al.* (1998) reported significant but inconsistent control of tomato bacterial spot (*Xanthamonas campestris* pv. *vesicatoria*) with NCT; 7-day fermentations made from either pine bark, cow manure, or yard waste composts varied in control between batches of the same compost source. After experimenting with various compost tea production methods it was suggested that control was due to an extractable, heat-stable metabolite produced within the compost pile. In this case, fermentation was not needed for suppression and the antibiotic agent(s) were inconsistently produced by identical composting practices. However, suppression did require the compost to be maintained at 55% minimum moisture content to generate suppression (Al-Dahmani, personal communication).

Numerous studies have shown that reducing the microbial component of NCT can negatively impact suppressive properties. When filter or heat sterilization results in the loss of disease suppression, it has been concluded that microbial competition for nutrients or space is the mode of action. Plant-pathogen systems demonstrating experimental evidence to support this conclusion include *Phytophthora infestans* on tomato and potato (Weltzien and Ketterer 1986b), *Uncinula necator* and *Plasmopora viticola* on grapes (Weltzien and Ketterer 1986a), and *Botrytis cinerea* on bean (Stindt 1990) and strawberries (Urban and Tränkner 1993). For example, NCT was filtered through increasingly smaller pore sizes (50, 10, 5, 1, 0.45, and 0.2 *u*m) with each filtrate sprayed onto detached tomato leaves followed 3 days later by *P. infestans* inoculation (Ketterer 1990). Suppression of *P. infestans* was not affected by 50 or 10 *um* filtration, but the 5.0 *u*m pore size reduced suppressive activity with further stepwise losses of suppression observed with smaller pore sizes. These studies indicate that applying the microbial component of compost tea is necessary for disease suppression. However, it is not clear whether pathogen inhibition is due to parasitism, competition for nutrients and colonization sites, or if applied organisms produce antibiotics *in situ* once established on plant surfaces.

Microbial Dynamics

Regardless of the mode of action, the total microbial population in NCT has been correlated to increased disease suppression. Ketterer (*et al.* 1992) related the suppression of *B. cinerea* on detached grape leaves to the total culturable microbial populations in the applied NCT. Three composts were fermented for one, three, seven and 14 days with seven days being the most suppressive and having the greatest population as determined by plating on caso agar. Heat sterilizing the NCT significantly reduced and nearly eliminated suppression.

The relative importance of the living microbial community for disease control can change as the duration of NCT fermentation increases. Stindt (1990) observed an inverse relationship between fermentation time and the role of microbial competition for suppressing *B. cinerea* on detached bean leaves. Fermentation periods of 4 to 16 days were equally suppressive, but heating the four day fermentation reduced suppression relative to heating the 16-day fermentation. In this example, microorganisms are necessary for antagonism early in the nonaerated fermentation process, whereas longer fermentations likely accumulate metabolic byproducts that play an increasing role in disease suppression.

A number of phylloplane studies have examined populations of microbes recovered from NCT treated leaves in relation to foliar disease levels. While investigating apple scab leaf severity in the field, Andrews (1993) compared culturable populations of fungi and bacteria from leaves treated with NCT to untreated leaves throughout two growing seasons. During a wet year no increase in phylloplane microbial population was detected, bacterial populations generally increased 1 log / g leaf during a dry year. However, no significant disease control was observed either season. Another study recovered phylloplane bacteria from apple trees treated with NCT mixed with 0.06% Latron B1956 spreader-sticker. Bacterial cfu / g leaf were ten-fold higher for 12 days post application compared to water treated leaves (Yohalem *et al.* 1996a). Lange and Weltzien (unpublished, reported in Tränkner and Brinton (1998)) observed a general increase in total culturable grape phylloplane populations three days post NCT application. Aerobic spore forming bacteria increased significantly by 1 log / g fresh leaf, coinciding with a 50% reduction in powdery mildew leaf disease severity.

The relationship of culturable leaf populations of yeasts and fungi, Enterobacteria, Pseudomonads, aerobic Bacillus spp., and total epiphytes to *Plasmopara viticola* (growth chamber) and *Uncinula necator* (vineyard) infected grape plants was studied (Sackenheim *et al.* 1994). Growth chamber and field plants were sprayed with various NCT, fermented with or without nutrients, and applied with or without methyl cellulose as a tank mixed surfactant. The growth chamber study was conducted at two relative humidity levels, 50-60% and 90-95%. Under lower humidity, leaf populations of all microbe groups except spore forming bacilli were drastically reduced across treatments and only treatments fermented with nutrients significantly reduced disease severity. This illustrates the need to screen potential treatments under a variety of environments. Under field conditions, all treatments significantly reduced powdery mildew severity compared to a water control. The combination of fermentation nutrients with methyl cellulose generated the greatest number of recovered organisms per leaf area, and only this treatment reduced disease significantly more than the basic NCT. Further evidence that increasing leaf microbial populations may be related to disease suppression has been shown in greenhouse experiments with bean rust (*Erisiphe polygoni*) and tomato late blight (*P. infestans*) (Ketterer and Schwager 1992). Plants treated with NCT had significantly increased leaf populations (cfu) of *Pseudomonas* spp., Enterobacteriaceae, and spore-forming bacteria, and these elevated populations were related to reduced disease. The greatest increases in culturable leaf populations were observed when casein (0.5% w:v) was added to the NCT just before application. Increasing microbial populations through the addition of fermentation nutrients, and using spray adjuvants to increase phylloplane survival, likely optimizes conditions for multiple modes of antagonistic activity.

Understanding Variable Efficacy

Microbial populations in compost tea are considered the most significant factor contributing to disease suppression. However, despite their importance, there is a very limited understanding of the microbial species composition of compost tea and how these organisms survive on plant surfaces. This limited knowledge likely contributes to the variable success reported for controlling plant pathogens with compost tea. Additionally, standardized methods for reporting on compost tea microbiology have not been established and this hinders comparison across experimental systems. Examining our current knowledge of compost tea microbiology, its impact on leaf surface microbial ecology, and the methods used thus far for studying these populations can help identify causes for variability in disease control efficacy and point to future research needs.

It is possible that efficacy is linked to the total microbial population or specific subpopulations in compost tea. In theory, if all microbial species in compost tea could function towards disease suppression, then higher total microbial counts or biomass should correlate to more consistent disease control or allow greater dilution rates to be used. The total culturable bacteria reported for suppressive NCT vary over several orders of magnitude with a range of 10^7 to 10^{10} cfu/ml (Table 5.) This data could suggest that 10^7 cfu/ml total bacteria in compost tea is a minimum population threshold for foliar disease suppression to function. However, we have observed variable suppression of *Botrytis cinerea* on geranium foliage with both ACT and NCT that ranged from 10^7 to 10^9 cfu/ml total bacteria (Scheuerell and Mahaffee, unpublished data). This leads us to believe that the total culturable bacterial population in compost tea does not necessarily correlate to suppression. Variability in bacterial species might be a cause of variable efficacy results but more work is needed to establish a relationship between populations of specific organisms and disease control.

TABLE 5.
Aerobic colony forming units/ml for nonaerated compost tea[a].

Compost Type	Total cfu	Aerobic Bacteria	Entero-bacteriaceae	Actino-mycetes	Fungi and Yeasts	Source
Horse manure		1 x 10^7	2 x 10^5		1 x 10^5	Stindt, 1990
Horse manure	1.4 x 10^{10}					Ketterer, 1990
Horse manure	7.6 x 10^7					Ketterer *et al.* 1992
Cattle manure		6 x 10^8	2 x 106		5 x 10^5	Stindt, 1990
Cattle manure	2.8 x 10^8					Ketterer, 1990
Cattle manure	8.2 x 10^8					Ketterer *et al.* 1992
Grape marc		2 x 10^8	3 x 10^5		9 x 10^5	Stindt, 1990
Grape marc	3.1 x 10^{10}					Ketterer, 1990
Grape marc	7.4 x 10^7					Ketterer *et al.* 1992
Horse-chicken		5.6 x 10^{10}		2.4 x 10^5	1.1 x 10^2	McQuilken *et al.* 1994
Chicken manure			0.8			Welke, 1999
Cattle manure			35			Welke, 1999

[a]Compost:water ratios range from 1:5 to 1:9. Data are from 7-8 day fermentations with no added fermentation nutrients.

Attachment and survival of the microbes after application may be equally or more important than the initial microbial populations in compost tea for disease suppression. Little is known about the underlying principles that govern the adhesion and survivability of various types of compost tea organisms in the phyllosphere and rhizosphere. Applying NCT can have immediate impact on phylloplane microbial populations, but the longevity of microbial change is likely influenced more by environmental conditions than by properties of the NCT. Tränkner (1992) detected an increase of 10^3 cfu/cm^2 total microorganisms on greenhouse grown bean leaves 1 hour after NCT treatment. Under moist conditions, culturable phylloplane populations were maintained for at least five days, while total populations were significantly reduced under dry conditions to 10 cfu/cm^2. Applying NCT on field grown potato plants resulted in significant increases of Pseudomonads and Enterobacteria compared to a water control; however, total culturable microbial epiphytes did not differ (Tränkner 1992). These studies indicate that under changing environmental conditions the total microbial carrying capacity of foliage is not elevated for extended periods after applying compost tea when spray adjuvants are not used. However, it is possible for specific groups of organisms from compost tea to increase as a proportion of the total culturable epiphytic population. If these selected groups are suppressive against the targeted pathogen, then the likelihood of disease control increases.

Techniques utilized thus far for the study of compost tea microbial ecology have limited our understanding of the variability associated with suppression. To date, published investigations have relied on enumeration of culturable components of compost tea and phyllosphere microflora. While it is understood that using plate counts for estimating total microbial populations biases the results to culturable organisms and does not provide information on metabolic state (Tate 2000), plate counts are useful for tracking specific groups of organisms and provide a framework to relate findings to the existing phyllosphere and phytopathology literature.

It has been proposed that direct counts are the best method to assess compost tea bacteria and fungal populations, and that the addition of fluorescent stains can be used to assess metabolic state (Ingham 2000b). While they are useful for enumerating total populations, they do not allow for estimates of genetic or functional diversity. Thus impacts of various compost tea production methods on microbial diversity cannot be measured.

Interestingly, we have observed that estimates of total bacterial cells in ACT fermented with a variety of nutrients are statistically the same when measured by enumeration on agar media or by staining and direct microscopic counts (unpublished data). These results appear to indicate that the ACT fermentation process selects for culturable bacteria. However, when NCT is fermented with nutrients, aerobic plate counts are typically significantly lower than the total bacterial population estimated using staining and direct microscopic counts (unpublished data). This indicates that a large portion of the microbial population may be strict anaerobes or nonculturable facultative aerobes. Regardless, both direct count techniques and culture methods have severe limitations for tracking the changing microbial ecology of compost tea during production and after application to plant surfaces.

The role of microbial diversity in the efficacy of compost teas has not been examined. If specific microbial types can be linked to disease suppression then monitoring microbial diversity and abundance will be crucial for achieving consistent biological control. An integrated assessment combining culture methods with extensive molecular studies is necessary to determine the diversity and abundance of microbes present in compost tea, and most importantly, to understand how different compost tea production practices affect the microbial community and how these communities function in pathogen and/or disease suppression.

Regardless of the mode of action or source of microorganisms, preventative application before pathogen infection appears necessary for optimal control through all known modes of action. Blakeman and Fokkema (1982) state that most foliar pathogens susceptible to antagonism exhibit some superficial growth on the leaf surface from which penetration of the leaf surface takes place. This is a likely reason why many successful examples of *Botrytis cinerea* suppression with NCT have been documented. The many examples of powdery and downy mildew suppression (Table 3 and 4) could also relate to the large portion of exposed hyphae and reproductive structures accessible to applied microbes and metabolites. However, Stindt (1990) reduced *B. cinerea* infections after spraying NCT 24 hours post pathogen inoculation, indicating that eradicative treatments with compost teas may be possible. Maximizing the interaction time between pathogens and resident antagonists on plant surfaces will likely increase disease suppression. Once we have developed a better understanding of compost tea microbiology and the survival and interactions of microbes on plants surfaces, it should be possible to modify compost tea production practices and application technology to optimize delivery of a microflora with multiple modes of pathogen suppression.

Production Practices and Application Technology

Besides the role of aeration in compost tea production, several of the process steps (Table 1) can impact the suppressive properties of NCT. Influential production decisions include choice of compost feedstocks, compost age, water ratio, fermentation time, added nutrients, temperature and pH. Application technology choices include the dilution ratio, application equipment, timing, rates, spray adjuvants and adding specific microbial antagonists. As the body of published research expands, it becomes obvious that there is no one ideal management level across all host-pathogen systems for the compost tea production and application factors. Studies are highlighted that indicate where similarities and inconsistencies exist within these factors in relation to optimizing disease suppression with NCT. The emphasis is on NCT since few of these steps have been investigated for impacts on production of ACT. Less studied factors will be addressed in relation to the potential impact on disease suppressive qualities and indicate future directions of research.

Compost Feedstocks

Compost feedstocks can include animal manures and bedding, landscape and agricultural plant material, and soil. Each have characteristics that influence the biological and physical characters of a mature compost, which could in turn impact the efficacy of compost tea made from the compost. Early reports on NCT indicate that the most efficacious control was attained using animal manure composts as opposed to compost made solely from vegetative material (Weltzien 1990;1991).

The superiority of manure containing compost was supported when 32 different composts were screened for the *in vitro* inhibition of *V. inequalis* conidia; only composts containing undigested plant material were not efficacious (Andrews 1993). Contrary to this, Elad and Shtienberg (1994) determined that plant-based compost produced from grape marc was equally effective as manure based compost to make NCT that inhibited *B. cinerea* on foliage in greenhouse assays. While differences in compost source used for compost tea do translate to different levels of disease suppression in the field (Scheuerell and Mahaffee 2000b), the level of suppression could not be predicted by microbial enumeration on selective media.

Due to the potential for transferring detrimental effects, compost for compost tea should be certified free of human pathogens and residual herbicides. Raw manures should be avoided because of the potential of human pathogens being present. Herbicide contamination of compost tea is becoming a potential issue with the increasing occurence of clopyralid and picloram contaminated compost (Bezdecek *et al.* 2001; Rynk 2001). However, we are unaware of any reports indicating contamination of compost tea from herbicides in compost.

Compost Age

There is increasing knowledge on how old compost made from particular feedstocks can be before it is no longer useful for making suppressive NCT. Tränkner (1992) reviewed German studies that claim composts should be two to six months old when selected for use. In summarizing work by Dittmer *et al.* (1990) and Dittmer (1991), Brinton *et al.* (1996) indicate that compost made only with plant material such as leaves, yard trimmings and straw is not useful after aging three months while horse and dairy manure compost can be used until nine to 12 months old. In a cucumber downy mildew assay using NCT prepared with horse manure compost, six month-old compost was significantly more effective than one-year-old compost ((Winterscheidt *et al.* 1990) cited in Weltzien 1991)). Andrews (1993) reported that the efficacy of NCT for *in vitro* inhibition of *V. inaequalis* germination declined as cattle manure-straw compost aged from 12 to 18 to 24 months. In trying to extend the useful life of effective compost sources, air dried compost has been used to produce NCT that was equally effective as fresh compost for *B. cinerea* suppression (Urban and Tränkner 1993). Further work of this nature might allow effective compost to be dried and stored large quantities for future use. Thus, the effect of compost age on efficacy of compost tea is a factor of feed stocks and storage conditions. Although no compost tea research has documented the stability of compost used in trials, compost stability could be a more useful parameter to report than compost age.

Compost to Water Ratio

The ratio of compost to water on a volume:volume basis in published studies starts at 1:1 (Zhang *et al.* 1998) and reaches 1:50 Weltzien (1990). Most studies have followed the methodology developed by Weltzien's laboratory that uses a 1:3 – 1:10 ratio. Weltzien (1990) reviewed a number of host-pathogen systems that had significant foliar suppression with NCT, no difference in suppression was observed for fermentation ratios between 1:3 and 1:10. However, for the suppression of *Phytophthora infestans,* increasing the fermentation ratio to 1:50 resulted in loss of activity (Weltzien 1990). In general, diluting the final spray would likely have a different effect than diluting the initial fermentation ratio because the initial ratio can influence the rate of oxygen depletion during fermentation (Cronin *et al.* 1996; Merril and McKeon 2001). It is still unclear how the compost to water ratio of NCT impacts disease suppression, but limiting the ratio to 1:10 is apparently effective.

Fermentation Time

For NCT, several studies have indicated that disease suppression varies widely in relation to the fermentation time (Weltzien 1990). Optimum fermentation times are listed in Table 3. Minimum effective fermentation time has been as short as one day for *in vitro B. cinerea* inhibition (Urban and Tränkner 1993), or three days for *in vitro* inhibition of *V. inaequalis* conidia (Andrews 1993). Usually, a five to eight day and up to a 16 day fermentation time is needed for any level of disease control, which has been hypothesized to allow sufficient time for facultative anaerobes to dominate and for their metabolites to accumulate (Weltzien 1991). Several studies have indicated that suppressiveness increases with increasing fermentation time to a maximum and then declines. Ketterer (1990) indicated a three day fermentation time peaked inhibition of downey mildew (*Plasmopara viticola*) on detached grape leaves. Weltzien *et al.* (1987, cited in Weltzien 1988) found that a four to seven-day fermentation time was optimal for suppressing powdery mildew (*E. betae*) on sugar beet in laboratory studies. Ketterer *et al.* (1992) examined *Botytis* suppression on detached grape leaves with one, three, seven and 14-day fermentations of three composts, and suppression was uniformly maximized at seven days. These same composts uniformly suppressed grape berry infection by *B. cinerea* after eight days of fermentation. However, Elad and Shtienberg (1994) observed that NCT fermented for 14 days was consistently more suppressive towards *B. cinerea* than seven-day fermentations. Weltzien (1990) showed that late blight (*P. infestans*) lesions on detached tomato leaves were inhibited to the greatest degree by seven or 14-day fermentation as compared to one, two or 28 days. The maximum NCT fermentation times reported for significant disease suppression were two and four-months, observed in a commercial vineyard experiment that evaluated grape bunch rot (*B. cinerea*) control (Ketterer *et al. 1992*). The general trend for maximizing suppression depends primarily on the host-pathogen system and secondarily on the compost feedstock, but the ideal fermentation time may need to be determined for each host-pathogen-compost system.

Much less is known about the effect of fermentation time on efficacy of ACT. Cantisano (Cantisano 1998) states that one-day aerated fermentations are used for foliar feeding while maximum disease control is achieved with seven to 14 day ACT. On the other hand, Ingham (1999 2000b) states that the optimum ACT fermentation time coincides with maximum active microbial biomass during fermentation, often 18-24 hours with commercial aerobic compost tea makers.

Fermentation Nutrients

Optional nutrients can be added at the beginning or during fermentation resulting in an unknown selective enrichment of the fermenting community (Bess 2000). Several manufacturers of compost tea equipment also offer prepackaged fermentation nutrients; these typically contain molasses, soluble kelp, humic materials and lesser amounts of organic materials and minerals. While practitioners use a wide range of fermentation nutrients, including molasses, kelp, fish emulsion, rock dusts, and plant extracts (personal observation), it is not known what effect these nutrients have on disease suppression.

Reductions in disease levels have been attained by using fermentation nutrients in NCT production (Table 3), with added concentrations generally ranging up to 1%, but 3% sucrose has been used (Sackenheim, *et al.* 1994). Malt (1%) was fermented in horse manure NCT to increase suppression of *P. infestans* (Ketterer 1990). Urban and Tränkner (1993) report that fermenting with 5-7 g/l peptone or yeast extract inhibited *B. cinerea* up to 100% while starch and sucrose additions were less effective. However, Elad and Schtienberg (1994) found no significant increase in *B. cinerea* control with the addition of an unstated quantity of nutrient broth (Difco). One issue to using NCT fermented with added nutrients is that an offensive odor is often quite evident. We have observed that odor production is directly tied to nutrient addition, if no nutrient is added there is little offensive odor. A user friendly research focus for NCT production would be exploring nutrients that minimally increase offensive odors.

ACT production frequently uses fermentation nutrients (Table 1), with a number of recipes and commercial blends being used (Ingham 2000b). Ingham (Ingham 2000b) states that the final balance between bacteria and fungi in ACT can be predetermined by selecting appropriate compost and fermentation nutrients. However, after trying various recipes, we have been unable to produce ACT dominated by fungi. We have also encountered loss of suppression associated with the addition of nutrients. It is also possible that residual fermentation nutrients could stimulate pathogens that have an efficient saprophytic phase, thus negating suppressive effects of the compost tea. Batch fermentations that are terminated at the maximum metabolic activity level likely leave unfermented nutrients available to all organisms. This could counteract nutrient competition-mediated biocontrol. Identification of nutrients that facilitate multiplication of antagonists while not supporting growth of animal or plant pathogens is needed.

Other fermentation factors that could affect disease suppression include fermentation temperature and pH. For NCT, fermentation temperature has been reported to be within 15-21°C. No studies have manipulated the fermentation temperature to observe the effect on disease suppression, but temperature nonuniformly influences growth rate of microorganisms. It is also possible that matching the fermentation temperature to the targeted environment temperature could reduce the stress experienced by applied organisms.

The pH of ACT or NCT could impact the growth and diversity of organisms in compost tea, thereby influencing efficacy. In general, bacterial growth is favored by neutral pH while yeast and fungi are favored in alkaline and acid pH ranges (Schlegel 1993). Yohalem *et al.* (1994) reported that the pH of their NCT was consistently between pH 8.0 and 8.5 in an *in vitro* assay that assessed *V. inaequalis* conidia germination. Urban and Tränkner (1993) determined that the pH should be above six to optimize *in vitro* inhibition of *B. cinerea*. Nothing has been reported about the relationship between compost tea pH and field suppression. Once specific microbial antagonists are identified, it is possible that manipulation of pH during compost tea production could assist their enrichment and survival after application.

Application Technology and Timing

In considering how to most economically and conveniently use compost tea for disease suppression, it is important to know what types of application technology can be used, and whether tank mix fertilizers, dilution prior to spraying, storing before spraying or decreased spray frequencies are viable options. Virtually nothing is known about how conventional pesticide sprayers impact the delivery and viability of these complex microbial communities. It is possible that the mechanical action, rapid pressure changes, and sheer forces associated with sprayers can selectively affect components of the applied community. Various types of application equipment need to be tested for detrimental effects while strategies for application methodology and timing need to be optimized.

Fertilizers are sometimes added to compost tea before spraying. It is not known if fertilizer tank mixes cause undue osmotic stress on the microbial fraction of compost tea. It is also possible that a portion of the chelated micronutrients intended for foliar absorption are sequestered by microorganisms between mixing and application.

There is minimal data on the potential to dilute compost tea before use. All field trials have used NCT in undiluted form, while two reports (Elad and Shtienberg 1994; Yohalem *et al.* 1994) have examined dilution in greenhouse and *in vitro* studies. In a greenhouse study on pepper and tomato foliage, Elad and Shtienberg (1994) diluted various NCT's five-fold and 25-fold. They found that changes in efficacy varied across compost sources. Yohalem *et al.* (1994) determined in an *in vitro V. inaequalis* conidia germination assay that 10 and 100-fold dilutions of spent mushroom NCT maintained the inhibitory effect.

The possibility of storing NCT before use has been investigated. For suppression of conidia germination (*V. inaequalis*), NCT could be stored for up to four months at -20°C with no loss of efficacy, while decreasing efficacy was observed with -4°C storage, and further loss at room temperature storage (Yohalem *et al.* 1994). Urban and Tränkner (1993) freeze dried NCT, then used this material in four hour fermentations to produce NCT suppressive to *B. cinerea*. Length of storage could differentially affect disease suppression depending on the mode of action for a particular compost tea. If the mode of action is mainly due to competition, it could be more susceptible to reduction in efficacy with storage than if the mode of action is due to stable metabolites secreted into the water.

The minimum frequency of applying compost tea for effective disease suppression has not been systematically examined. It will probably depend more on plant growth, pathogen reproduction rates and dispersal mechanism, and environmental conditions than on characteristics of the compost tea. In a greenhouse study, Malathrakis *et al.* (1995) attained significant control of *B. cinerea* on all tomato plant parts by weekly applications of several NCT treatments made from different manures. In field studies, disease suppression has relied on regular applications, either weekly on annuals (Tsror 1999), or on seven to 14 day intervals from five to ten times per season during periods of high disease pressure in perennial crops (Ketterer 1990; Samerski 1989; Weltzien 1991). While spraying frequency has not been a variable in these studies, this intense frequency of application portrays a biological pesticide type of deployment, and does not indicate a sustained microbial shift on the phylloplane that is capable of self-regulating biological control. Timing applications with periods of low environmental stress, such as early morning, might help establish microbial epiphytes. The use of disease forecasting models that incorporate weather forecasts could also decrease the spray frequency by applying compost tea just before conditions become favorable for pathogen infection.

Perhaps the most promising application factors that can be modified for decreasing the spray frequency, and variability associated with suppression, are adding spray adjuvants and specific microbial antagonists. The use of surfactants, sticking agents, and UV inhibitors is a common practice in chemical pesticide formulation and application (Backman 1978), but it has received scant attention in the biological control literature. The potential antagonistic efficacy of NCT can be increased with commercial spreader-sticker agents, as recommended by Brinton *et al.* (1996). However, spray adjuvants can inhibit microbial activity and this could affect the targeted pathogen and/or antagonists (Brinton *et al.* 1996). We have observed more uniform distribution and adherence of ACT bacteria on leaf surfaces due to the addition of spreader-stickers (Scheuerell and Mahaffee 2000a). The addition of methyl cellulose to NCT has already been discussed in relation to increasing suppression of grape vine powdery mildew (Sackenheim *et al.* 1994). However, under severe disease pressure, further reduction in apple scab severity by NCT was not attained by adding either Latron B1956 (0.06% v:v) spreader-sticker or fish oil (0.025%) to NCT (Yohalem *et al.* 1996a). Tränkner and Brinton (1998) reported that field control of grape powdery mildew was reduced from 62% to 8% by adding 0.5% CASO bouillon and 0.05% rape seed oil prior to applying a horse manure NCT. Using microbial nutrient substrates to increase adhesion of compost tea organisms, and subsequent phylloplane growth, deserves more attention. By tank mixing 0.5% casein as a protein source for organisms in NCT, Ketterer and Schwager (1992) observed decreased levels of *E. polygoni* on bean and *P. infestans* on tomato equal to that obtained by applying the fungicides propineb or sulfur.

The general foliar biological control literature indicates that a number of studies have applied specific bacterial antagonists with nutrients to enhance leaf colonization and survival (Andrews 1992). Most often, addition of foliar nutrients has resulted in a transient spike of the total culturable microbial epiphyte population without selecting for the applied antagonist. However, increased control of early leafspot (*Cercospora arachidicola*) of peanut was observed by applying chitinolytic *Bacillus cereus* with chitin and a sticking adjuvant. The population of both the applied organism and the total chitin degrading bacterial community were selectively increased and maintained above background levels (Kokalis-Burrelle *et al.* 1992). It is also possible that the effect of adding microbial growth substrates on pathogen suppression depends on the life strategy of individual pathogens. Thus far, adding nutrient adjuvants to compost tea to increase the suppression of foliar pathogens has been limited to biotrophic pathogens. These biotrophs are not enhanced by added foliar nutrients. Other pathogens with significant saprophytic activity, or those requiring exogenous nutrients for germination, could be enhanced by nutrient addition. Since the addition of various adjuvants can have either beneficial or detrimental effects on the efficacy of compost teas, each type needs to be assessed for their effects on the compost tea community, as well as on the plant and pathogen.

The addition of specific antagonistic microorganisms to compost tea can potentially increase the disease suppressive properties. Cultured antagonists were combined with NCT immediately before spraying in field studies on *P. viticola* on grapevine and *P. infestans* on potato (Ketterer 1990). In both cases, seven pure cultures of antagonists (four fungi, two bacteria, one yeast) that had been isolated from NCT treated potato leaves, were increased, mixed, and then added 2% by volume to the NCT. Both trials achieved suppression equal to a fungicide control, although for *P. viticola*, ten applications of the microbial amended NCT were comparable to five fungicide applications. It is possible that combining commercial biological control strains with compost tea could provide more consistent suppression than either component alone. This could be the case if the compost tea microflora assists the colonization and survival of the biocontrol strain through biofilm formation on plant surfaces.

Future Developments

There are a number of developments unrelated to plant disease control that will potentially impact how practitioners make and use compost tea. Two of the most pertinent issues are the development of compost tea standards and the potential for human pathogen growth during fermentation.

Compost Tea Standards

An increasing number of businesses are selling compost tea to gardeners and growers. However, it is difficult for buyers to be assured of the product contents or functions because there are no standards for determining the suitability of compost tea for a particular use. Thus far only one set of standards has been proposed (Table 6) this proposal addresses three main criteria, minimum oxygen content, passing *in vitro* pathogen inhibition assays, and minimal populations of organisms (Ingham 2001b). Whether a minimum oxygen level needs to be set for ACT is not clear; it does not appear to be needed for NCT since they are produced without aeration and are highly efficacious against a wide range of plant diseases (Table 3).

TABLE 6.
Proposed minimum standards for assessment of compost tea quality
(reprinted from Ingham, 2001b)

Proposed Compost Tea Standard	Standard Specifications
Oxygen concentration during compost tea production	Remain above 5.5 ppm, or 60% dissolved oxygen (15% O_2 as part of total gases) when at sea level and room temperature.
In vitro Pathogen Inhibition Assay - BBC Labs (www.bbclabs.com) The pathogens to be tested need to be specified based on foliar or soil applications. A report from BBC Labs indicating that at least 75% of the pathogens in the test group were inhibited.	Foliar pathogens are Alternaria, Botrytis, Colletotrichium, Drechslera, Erwinia and Verticillium. Soil pathogens are Armillariella or Sclerotinia, Fusarium Gaumannomyces or Sclerotium, Phytophthora, Pythium, Rhizoctonia.
Total and Active Bacteria; Total and Active Fungi - SFI (www.soilfoodweb.com) Data from Soil Foodweb Inc. indicating that the desired range of both bacteria and fungi were produced in the tea. Minimum levels of all necessary organisms, per ml, when 5 gallons compost tea to the acre is applied, are:	10 to 150 ug active bacteria; 150 to 300 ug total bacteria; 2 to 10 ug active fungi; 5 to 20 ug total fungi; 1000 flagellates*; 1000 amoebae*; 10 ciliates*; 10 nematodes*; *Protozoa and nematodes may not be critical in foliar applications

It is well known that *in vitro* inhibition often correlates poorly with field performance of foliar biological control agents (Andrews 1985; Cook and Baker 1983). Assessing germination of pathogenic spores by compost tea has limitations; *In vitro* inhibition of conidia germination of *V. inaequalis* did not correlate to apple scab control in the field (Andrews 1993). The nutrient agars typically used in *in vitro* assays do not represent the distribution and abundance of leaf surface nutrients (Derridj 1996). Antibiotic production observed in agar culture may not be expressed in various environments (Bonsall *et al.* 1997; Duffy and Defago 1999). No laboratories performing *in vitro* inhibition assays have published their database on the relationship between *in vitro* inhibition and field performance of compost tea, therefore, it is difficult to independently assess the utility of these assays.

In relation to minimum microbial populations, it has been stated that microscopic examination of leaf surfaces treated with compost tea is a superior method of predicting foliar disease control (Ingham 2000b and 2001a). It is stated that if leaf surfaces are covered by at least 60-70 percent active bacteria and 2-5% active fungi (determined by epifluorescent examination of leaf sections stained by fluorescein diacetate) no colonization of the plant surface by a plant pathogen can occur (Ingham 2000b and 2001a). Direct visualization of treated leaf surfaces will likely be an important research tool for understanding the spatial distribution of applied microorganisms and pathogens. However, assays that analyze spatial distribution of applied organisms do not account for the potential of metabolites, produced during fermentation, to affect pathogens or for the potential of induced resistance. Before minimum microbiology standards are set, it is necessary to have replicated field data from a diverse range of production systems and environments to assess how proposed standards correlate to field performance.

Potential for Supporting Human Pathogen Growth

Yohalem *et al.* (1994) raised the concern that fermenting compost could potentially support the growth of enteric pathogens, evidenced by the Enterobacteriaceae cfu from NCT reported by Urban and Tränkner (1993). Enterobacteriaceae cfu were greater with the addition of 10g/l yeast extract at the start of the 24 hour fermentation (Urban and Tränkner 1993). While not all Enterobacteriaceae are human pathogens, their populations are often used as indicators that human pathogens may be present (Murray 1999). Welke (1999) tracked fecal coliform and *Salmonella* populations from the source compost, through NCT fermentation, to samples of broccoli and leek sprayed and grown under field conditions (Table 7). The data suggests that human pathogens can be transferred from naturally contaminated compost to food surfaces with NCT.

Statements have been made that human pathogens generally grow better under anaerobic or reduced oxygen tension, and that pathogen regrowth will not occur in highly aerated (>5.5 ppm O_2) ACT systems in the presence of competing microflora (Ingham 2000b 2001a). However, the majority of enteric human pathogens — particularly common gastrointestinal infecting genera such as *Escherichia, Salmonella, Shigella,* and *Yersinia* — are most commonly isolated and grown under aerated conditions (Murray 1999). Additionally, we have preliminary evidence indicating a variety of enteric pathogens can increase during ACT and NCT production, if fermentation nutrients are used in conjunction with compost that has been inoculated with pathogens (Scheuerell, Mahaffee, Millner and Ingram, unpublished data). Pathogen growth does not appear to be supported when ACT or NCT is made without fermentation nutrients. Similar results have been observed with ACT made from compost that naturally contained a low level of *E. coli* (Bess *et al.* 2002). Their results suggest that naturally occurring *E. coli* can be reduced or

TABLE 7.
Fecal coliform and Salmonella data from Welke (1999)

	Chicken Manure Compost		Cattle Manure Compost	
Sample material	Fecal coliforms	Salmonella	Fecal coliforms	Salmonella
Compost	< 3 MPN/g	Not detected	930 MPN/g	Not detected
8 day nonaerated compost tea, no fermentation nutrients added	0.8 cfu/ml	Not detected	35 cfu/ml	Not detected
Broccoli tissue	3 MPN/g	Not detected	<3 MPN/g	Not detected
Leek tissue	43 MPN/g	Not detected	<3 MPN/g	Not detected

eliminated by avoiding the addition of sugars during ACT production. Other work by Duffy (*et al.* 2002) examined the growth potential of *Salmonella enterica* and *E. coli* O157:H7 inoculated at 1 cfu/ml into flasks containing 20 g compost, 180 ml sterile water, and 0-1% molasses, then rotary shaken (100 rpm 20 C) for three days. Pathogen growth was not observed in the absence of molasses. There was a positive correlation between the growth of pathogens and molasses concentration.

It appears that adding fermentation nutrients, especially those high in sugar, is a greater factor than oxygen concentration governing the growth of enteric pathogens in compost tea. Detailed studies are needed to determine if recalcitrant, complex fermentation nutrients can be used that increase antagonists while not supporting the growth of pathogens. However, if enteric pathogens were to inadvertently grow in compost tea, the fate of these applied enterics needs to be determined, on plant surfaces under field conditions, in order to judge the potential risks of exposing consumers to pathogens (Suslow 2002). Enteric pathogens would pose a potential health risk to spray applicators and appropriate personal protection equipment should be used. As a precautionary measure, compost used for compost tea production should be tested for the presence of human pathogens. The need to further assess the human health risk posed by the use of compost teas has been addressed in the final rules of the National Organic Program administered by the USDA Agricultural Marketing Service (NOP 2002). While no specific recommendations regarding the production or use of compost tea are included in the final rule, previous recommendations by the Compost Task Force of the National Organic Standards Board stated that compost tea be made with compost that has met criteria for pathogen destruction (131°F for three days) or contain less than 3 MPN salmonella per 4 g dry wt compost and less than 1000 MPN fecal coliforms. In addition, the recommendation stated that readily available carbon sources such as sugars and molasses not be used as fermentation nutrients for compost tea production (NOSB 2002).

Conclusions

There is a pressing need to find sustainable approaches to managing plant diseases for both conventional and organic producers. Use of compost teas is being pursued as such an approach. Numerous reports from both practitioners and the scientific community reveal disease suppression using compost teas. For some plant diseases, the level of control is considered inadequate for conventional agriculture (Yohalem *et al.* 1996); however, organic producers with limited control options consider partial disease control to be an important improvement. Since most of the recent observations on beneficial effects are from growers, following their observations with replicated field trials will illuminate the extent that compost teas will provide a reliable disease management tool in the future.

We speculate that stabilizing suppressive activity will require identification of the active microbes, modification of compost tea production steps to ensure their presence, and the use of application technology including spray adjuvants to optimize delivery and survival of the desired organisms. Understanding modes of antagonistic activity could help combine compost tea with other biological and chemical agents in integrated control programs. In particular, fungicide resistance management programs could benefit from observations that NCT made from both cattle and horse manure composts suppressed fungicide resistant strains of *B. cinerea* (Stindt 1990).

Ultimately, compost tea is only one tool, and must be used within a system that incorporates plant resistance, optimal nutrition, sanitation, disease forecasting and minimizes plant stress. As recently recognized by the USDA Cooperative State Research, Education, and Extension Service, "Research on agricultural production components such as biocontrol and cropping systems has been of limited value to organic farmers, since the components are generally not developed and tested in an organic agro-ecosystem, and research results and recommendations thus can not be applied directly to organic farms" (Federal Register 2001). Thus, the use of compost tea as part of an integrated plant health management strategy will require much additional whole systems research by a cohesive team of farmers and experts in composting, plant pathology, phyllosphere biology, molecular microbial ecology, fermentation science, plant physiology, plant breeding, soil science and horticulture. The first step is having all interested groups review the range of reports and published research on compost tea use in order to facilitate an informed discussion to prioritize future collaboration.

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