Suppression of Plant Diseases by Composts

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During the 1960s, nurserymen across the United States explored the possibility of using composted tree bark as peat substitutes to reduce potting mix costs. Early during the utilization of bark composts, improved plant growth and decreased losses caused by *Phytophthora* root rots were observed as side benefits in the nursery industry. Today it is recognized that control of such root rots with composts can be as effective as that obtained with fungicides (Hardy and Sivasithamparam, 1991; Hoitink et al., 1991; Ownley and Benson, 1991). Therefore, the ornamental plant industry relies heavily on compost products for control of diseases caused by these soilborne plant pathogens. Composts have replaced methyl bromide in this industry (Quarles and Grossman, 1995). In field applications of composts, similar results have been obtained (Hoitink and Fahy, 1986; Lumsden et al., 1983; Schüler et al., 1993). Examples of diseases controlled by composts are reviewed in Hoitink and Fahy (1986).

Composts must be of consistent quality to be used successfully in biological control of diseases of horticultural crops, particularly if used in container media (Inbar et al., 1993). The rate of respiration is one of several procedures that can be used to monitor stability of composts (Iannotti et al., 1994). Variability in compost stability is one of the principal factors limiting its widespread use. Maturity is less important in ground bed or field agriculture as long as the compost is applied sufficiently ahead of planting to allow for additional stabilization; however, lack of maturity frequently causes problems here as well.

Effects of chemical properties of composts on soilborne disease severity often are overlooked (reviewed in Hoitink et al., 1991). Highly saline composts enhance *Pythium* and *Phytophthora* diseases unless they are applied months ahead of planting to allow for leaching. Composts prepared from municipal sewage sludge have a low C : N ratio. They release considerable amounts of N and enhance *Fusarium* wilt (Hoitink et al., 1987). On the other hand, composts from high C : N materials, such as tree barks, immobilize N and suppress *Fusarium* diseases if colonized by an appropriate microflora (Trillas-Gay et al., 1986). High ammonium and low nitrate nutrition increases *Fusarium* wilts (Schneider, 1985). Perhaps the low C : N in predominantly ammonium-nitrogen-releasing sludge compost enhances *Fusarium* diseases for this reason.

FATE OF BIOCONTROL AGENTS DURING COMPOSTING

The composting process is often divided into three phases. The initial phase occurs during the first 24 to 48 h as temperatures gradually rise to 40 to 50 °C, and sugars and other easily biodegradable substances are destroyed. During the second phase, when high temperatures (55 to 70 °C) prevail, less biodegradable cellulosic substances are destroyed. Thermophilic microorganisms predominate during this part of the process. Plant pathogens and seeds are killed by the heat generated during this high-temperature phase (Bollen 1993; Farrell 1993). Compost piles must be turned frequently to expose all parts to high temperature to produce a homogeneous product free of

pathogens and weed seeds. Unfortunately, most beneficial microorganisms also are killed during the high-temperature phase of composting.

Curing begins as the concentration of readily biodegradable components in wastes declines. As a result, rates of decomposition, heat output and temperatures decrease. At this time, mesophilic microorganisms that grow at <40 °C recolonize the compost from the outer low-temperature layer into the compost windrow or pile. Therefore, suppression of pathogens and/or disease is largely induced during curing, because most biocontrol agents recolonize composts after peak heating also.

Bacillus spp., *Enterobacter* spp., *Flavobacterium balustinum* 299, *Pseudomonas* spp., other bacterial genera and *Streptomyces* spp., as well as *Penicillium* spp., several *Trichoderma* spp., isolates of *Gliocladium virens*, and other fungi have been identified as biocontrol agents in compost-amended substrates (Chung and Hoitink 1990; Hadar and Gorodecki, 1991; Hardy and Sivasithamparam 1991; Hoitink and Fahy 1986; Nelson et al., 1983; Phae et al., 1990). The moisture content of compost critically affects the potential for bacterial mesophiles to colonize the substrate after peak heating. Dry composts (<34% moisture, w/w) become colonized by fungi and are conducive to *Pythium* diseases. To induce suppression, the moisture content must be high enough (at least 40% to 50%, w/w) so that bacteria, as well as fungi, colonize the substrate after peak heating. Water must often be added to composts during composting and curing to avoid the dry condition. pH also affects the potential for beneficial bacteria to colonize composts. A pH <5.0 inhibits bacterial biocontrol agents (Hoitink et al., 1991).

Variability in suppression of *Rhizoctonia* damping-off and *Fusarium* wilt encountered in substrates amended with mature composts is due, in part, to random recolonization of compost by effective biocontrol agents after peak heating. Field compost more consistently suppresses *Rhizoctonia* diseases than the same compost produced in a partially enclosed facility where few microbial species survive heat treatment (Kuter et al., 1983). Compost produced in the open near a forest (field compost), an environment that is high in microbial species diversity, is colonized by a greater variety of biocontrol agents than the same produced in an in-vessel system (Kuter et al., 1983). Frequently, however, *Rhizoctonia* and other diseases are observed for some time after composts are first applied (Kuter et al., 1988; Lumsden et al., 1983). Three approaches can be used to solve this problem: 1) Curing of composts for four months or more, rendering composts more consistently suppressive (Kuter et al., 1988); 2) incorporating composts into field soils for several months before planting (Lumsden et al., 1983); 3) inoculating composts with specific biocontrol agents (Kwok et al., 1987).

A specific strain of *Flavobacterium balustinum* and an isolate of *Trichoderma hamatum* have been identified that induce consistent levels of suppression to diseases caused by a broad spectrum of plant pathogens, if inoculated into compost after peak heating, but before significant levels of recolonization have occurred (Fig. 1). Patents have been issued to The Ohio State Univ. for this process (Hoitink, 1990). In Japan, Phae et al. (1990) isolated a *Bacillus* strain that induces predictable biological control in composts. It has been recognized for decades that single strains are not as effective in biological control in field applications as mixtures of microorganisms (Garrett, 1955). The same applies to container media (Kwok et al., 1987).

MECHANISMS OF SUPPRESSION IN COMPOSTS

Two classes of biological control mechanisms known as "general" and "specific" suppression have been described for compost-amended substrates. The mechanisms involved are based on competition, anti-

Received for publication 28 Mar. 1996. Accepted for publication 23 May 1996. Salaries and research support provided by State and federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State University, and by Grant no. US2196-22 from BARD, the U.S.-Israel Binational Research and Development Fund. Manuscript No. 79-96. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

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Fig. 1. Biological control of *Rhizoctonia* damping-off of radish (*Rhaphanus sativus* L.) in a natural composted pine bark and a biocontrol agent-fortified composted pine bark-amended potting mix. V = control without *Rhizoctonia*. Au R = sterilized mix infested with *Rhizoctonia*. R = Natural compost-amended mix infested with *Rhizoctonia*. Note losses similar to those in the sterilized mix. R + T₃₈₂ + F₂₉₉ = Biocontrol agent (*Trichoderma hamatum* 382 and *Flavobacterium balustinum* 299)-fortified mix. Note control induced by this treatment.

biosis, hyperparasitism, and the induction of systemic acquired resistance in the host plant. Propagules of plant pathogens, such as *Pythium* and *Phytophthora* spp., are suppressed through the "general suppression" phenomenon (Boehm et al., 1993; Chen et al., 1988a, 1988b; Cook and Baker 1983; Hardy and Sivasithamparam, 1991; Mandelbaum and Hadar, 1990). Many types of microorganisms present in compost-amended container media function as biocontrol agents against diseases caused by *Phytophthora* and *Pythium* spp. (Boehm et al., 1993; Hardy and Sivasithamparam, 1991). Propagules of these pathogens, if inadvertently introduced into compost-amended substrates, do not germinate in response to nutrients released in the form of seed or root exudates. The high microbial activity and biomass caused by the "general soil microflora" in such substrates prevents germination of spores of these pathogens and infection of the host (Chen et al., 1988a; Mandelbaum and Hadar, 1990). Propagules of these pathogens remain dormant and are typically not killed if introduced in compost-amended soil (Chen et al., 1988a; Mandelbaum and Hadar, 1990).

An enzyme assay that determines microbial activity based on the rate of hydrolysis of fluorescein diacetate (FDA) predicts suppressiveness of potting mixes to *Pythium* diseases (Boehm and Hoitink 1992; Chen et al., 1988a; Mandelbaum and Hadar 1990; You and Sivasithamparam, 1994). Similar information has been developed for soils on "organic farms" where soilborne diseases are less prevalent (Workneh et al., 1993). The length of time that the suppressive effect lasts also may be determined with FDA activity (Boehm and Hoitink, 1992). This is known as the "carrying capacity" of the substrate relative to biological control (Boehm et al., 1993).

The mechanism of biological control for *Rhizoctonia solani* in compost-amended substrates is different from that of *Pythium* and *Phytophthora* spp. because only a narrow group of microorganisms is capable of eradicating *R. solani*. This type of suppression is referred to as "specific suppression" (Hoitink et al., 1991). *Trichoderma* spp., including *T. hamatum* and *T. harzianum*, are the predominant fungal parasites recovered from composts prepared of lignocellulosic wastes (Kuter et al., 1983; Nelson et al., 1983). Parasites are microorganisms capable of colonizing plant pathogens resulting in lysis or death. These fungi interact with various bacterial strains in the biological control of *Rhizoctonia* damping-off (Kwok et al., 1987). It is of interest that *Penicillium* spp. are the predominant fungal parasites recovered from sclerotia of *Sclerotium rolfsii* in composted grape pomace, a high sugar and low cellulose content waste (Hadar and Gorodecki, 1991). *Trichoderma* spp. were not recovered from this compost and were not effective when introduced. The composition of the feed stock, as expected, appears to have an impact on the microflora in composts active in biological control.

BIOLOGICAL ENERGY AVAILABILITY VS. SUPPRESSIVENESS

The decomposition level of organic matter in compost-amended substrates has a major impact on disease suppression. For example, *R. solani* is highly competitive as a saprophyte (Garrett, 1962). It can utilize cellulose and colonize fresh wastes but not low-cellulose mature compost (Chung et al., 1988). *Trichoderma*, an effective biocontrol agent of *R. solani*, is capable of colonizing fresh as well as mature compost, but it grows better in fresh compost (Chung et al., 1988; Nelson et al., 1983). In fresh, undecomposed organic matter, biological control does not occur because both the pathogen and the biocontrol agent grow as saprophytes. Therefore, *R. solani* (the pathogen) remains capable of causing disease here. Presumably, synthesis of lytic enzymes involved in hyperparasitism of pathogens by *Trichoderma* is repressed in fresh organic matter due to high glucose concentrations in such waste (de la Cruz et al., 1993). The same processes may occur in antibiotic production, which also plays an important role in biocontrol.

In mature compost, where concentrations of free nutrients are low (Chen et al., 1988a), sclerotia of *R. solani* are killed by the hyperparasite, and biological control prevails (Nelson et al., 1983). The foregoing reveals that composts must be adequately stabilized to reach that decomposition level where biological control is feasible. In practice, this occurs in composts (tree barks, yard wastes, etc.) that have been 1) stabilized far enough to avoid phytotoxicity and 2) colonized by the appropriate specific microflora. Practical guidelines that define this critical stage of decomposition in terms of biological control are not yet available. Industry presently controls decomposition level by maintaining constant conditions during the entire process and adhering to a given time schedule. Composted pine bark produced by such a process has been used with great success in floriculture, indicating that this approach to quality control is quite acceptable (Hoitink et al., 1991).

Excessively stabilized organic matter, the opposite end of the decomposition scale, does not support adequate activity of biocontrol agents. As a result, suppression is lacking and soilborne diseases are severe, as in highly mineralized soils where humic substances are the predominant forms of organic matter (Workneh et al., 1993). The length of time that soil-incorporated composts support adequate levels of biocontrol activity has not yet been determined. Presumably, it varies with soil temperature, soil characteristics, and the type of organic matter from which the compost was prepared. Loading rates and farming practices of course also play a role.

We have studied the "carrying capacity" of soil organic matter in potting mixes prepared with sphagnum peat to bring a partial solution to this problem (Boehm and Hoitink 1992; Boehm et al., 1993). Sphagnum peat typically competes with compost as a source of organic matter in horticulture. Both the microflora and the organic matter in peat itself can affect suppression of soilborne diseases. The literature on that effect is reviewed briefly here.

Dark, more decomposed sphagnum peat, harvested from a 1.2 m or greater depth in most peat bogs, is low in microbial activity and consistently conducive to *Pythium* (Fig. 2) and *Phytophthora* root rots (Hoitink et al., 1991; Boehm and Hoitink, 1992). However, light, less decomposed sources of sphagnum peat, harvested from near the surface of peat bogs, have a higher microbial activity (FDA activity) and suppress root rot. Unfortunately, the suppressive effect of light peat to *Pythium* root rots is of short duration. (Boehm and Hoitink, 1992; Tahvonen, 1982; Wolffechele 1988). Light peats are used most effectively for short production cycles (6- to 10-week crops), such as in plug and flat mixes used in the ornamentals industry. Composts have longer lasting effects (Boehm and Hoitink, 1992; Boehm et al., 1993; You and Sivasithamparam, 1994).

As mentioned above, the rate of hydrolysis of FDA predicts suppressiveness of peat mixes and of compost-amended substrates to *Pythium* root rot (Boehm and Hoitink, 1992). As FDA activity, expressed as FDA hydrolyzed, in suppressive substrates declines to $<3.2 \mu\text{g}\cdot\text{min}^{-1}\cdot\text{g}^{-1}$ dry weight mix, the population of *Pythium ultimum* increases, infection takes place and root rot develops. During this collapse in suppressiveness, the composition of bacterial species also

Fig. 2. Biological control of *Pythium* root rot of poinsettia (*Euphorbia pulcherrima* Willd. ex Kl.) in a composted pine bark potting mix. Photograph was taken 35 days after planting of poinsettia rooted cuttings in mixes infested with *Pythium ultimum*. Top row = severe root rot in a disease-conducive dark, decomposed sphagnum peat mix. Middle row = mild root rot in a suppressive less decomposed light sphagnum peat mix. Bottom row = bio-control of root rot in a composted pine bark mix. (Figure from Hoitink et al., 1991).

changes (Boehm et al., 1993). A microflora typical of suppressive soils, which includes *Pseudomonas* spp. and other rod-shaped Gram negative bacteria as the predominant rhizosphere colonizers, is replaced by pleomorphic Gram-positive bacteria (e.g., *Arthrobacter*) and putative oligotrophs (Wu et al., 1993). The microflora of the conducive substrate resembles that of highly mineralized niches in soil (Kanazawa and Filip, 1986).

Nondestructive analysis of soil organic matter, utilizing Fourier Transform Infra Red spectroscopy (FT-IR) and Cross Polarization Magic Angle Spinning -¹³Carbon Nuclear Magnetic Resonance Spectroscopy (CPMAS - ¹³C NMR), allows characterization of biodegradable components of soil organic fractions (Chen and Inbar, 1993; Inbar et al., 1989). CPMAS - ¹³C NMR allows quantitative analysis of concentrations of readily biodegradable substances, such as "carbohydrates" (hemicellulose, cellulose, etc.) vs. lignins and humic substances, in soil organic matter (reviewed in Chen and Inbar, 1993). In a preliminary report, Wu et al. (1993) reported that the "carbohydrates" decline as suppressiveness is lost. During the same time period, bacterial genera capable of causing biological control are replaced by those that cannot provide control. Biocontrol agents inoculated into the more decomposed substrate are not able to induce sustained biological control of *Pythium* root rot. The same phenomenon has been observed for *Phytophthora* root rot in the field (You and Sivasithamparan, 1994). Therefore, biocontrol of these diseases is determined by the "carrying capacity" of the substrate, which regulates species composition and activity and, in turn, the potential for sustenance of biological control.

COMPOST FOR CONTROL OF FOLIAR DISEASES

During the past decade, a series of projects have been published on the control of plant diseases of aboveground plant parts with water extracts, also known as steepages, prepared from composts (Weltzien, 1992; Yohalem et al., 1994). Steepages often are prepared by soaking mature composts in water (still culture; 1:1, w/w) for 7 to 10 days. The

steepage is filtered and then sprayed on plants. Efficacy varies with the compost, batches of steepages produced, crops, and the disease under question. Sackenheim (1993), using plate counting procedures, has reported that aerobic microorganisms predominate in steepages. The microflora includes strains of bacteria and isolates of fungi already known as biocontrol agents. He developed several enrichment strategies that include nutrients and microorganisms to improve efficacy of the steepages.

Control induced by compost steepages has also been attributed to systemic acquired resistance (SAR) induced in plants by microbes present in the extracts (Weltzien, 1992). The recent work by Sackenheim (1993) on grape (*Vitis vinifera* L.), however, does not support this assumption. A factor that has not been evaluated, but could play a role in efficacy of steepages, is the condition of soil organic matter and the associated microflora in the soil in which treated plants are produced. Soils naturally suppressive to soilborne plant pathogens (e.g., compost-amended soils) harbor active populations of biocontrol agents (Boehm et al., 1993). Several of these rhizobacteria and fungi can induce protection to foliar pathogens in the leaves of plants (Maurhofer et al., 1994; Wei et al., 1991). Zhang et al., (1994) reported that pathogenesis-related proteins were activated in roots and shoots of cucumber plants produced in compost. Further work may reveal that composts affect resistance of the roots and foliage to diseases. Presently, control of foliar diseases with composts or steepages is highly variable.

DISEASE SUPPRESSION—OUTLOOK

Success in biological control of diseases with composts is possible only if all factors involved in the production and use of composts are defined and kept consistent. Most composts are variable in quality. Therefore, composted pine bark remains the principal compost used for the preparation of potting mixes or soils naturally suppressive to soilborne plant pathogens. Composted manures, yard, and food wastes are steadily gaining in popularity, and offer the same potential (Gorodecki and Hadar, 1990; Grebus et al., 1994; Inbar et al., 1993; Marugg et al., 1993; Schüler et al., 1993).

Controlled inoculation of composts with biocontrol agents is a procedure that must be developed on a commercial scale to induce consistent levels of suppression to pathogens such as *R. solani* (Grebus et al., 1993; Hoitink et al., 1991; Phae et al., 1990). Recently, tree bark was proposed as a food base for the culture of biocontrol agents and as a carrier of such agents for use in agricultural applications (Steinmetz and Schönbeck, 1994). However, this new field of biotechnology is still in its infancy. Major research and development efforts will need to be directed toward this approach for disease control. Recycling through composting is being chosen as the preferred strategy for waste treatment. This also applies to farm manures. For this reason, composts are becoming available in greater quantities. Peat, in contrast, is a limited resource that cannot be recycled. Future opportunities for natural and controlled-induced suppression of soilborne plant pathogens appear bright.

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