Effect of Potting Mix Microbial Carrying Capacity on Biological Control of Rhizoctonia Damping-Off of Radish and Rhizoctonia Crown and Root Rot of Poinsettia

Matthew S. Krause, Laurence V. Madden, and Harry A. J. Hoitink

Department of Plant Pathology, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster 44691.
Accepted for publication 1 August 2001.

ABSTRACT

Krause, M. S., Madden, L. V., and Hoitink, H. A. J. 2001. Effect of potting mix microbial carrying capacity on biological control of Rhizoctonia damping-off of radish and Rhizoctonia crown and root rot of poinsettia. *Phytopathology* 91:1116-1123.

Potting mixes prepared with dark, highly decomposed Sphagnum peat, with light, less decomposed Sphagnum peat, or with composted pine bark, all three of which were colonized by indigenous microorganisms, failed to consistently suppress Rhizoctonia damping-off of radish or Rhizoctonia crown and root rot of poinsettia. Inoculation of these mixes with *Chryseobacterium gleum* (C₂₉₉R₂) and *Trichoderma hamatum* 382 (T₃₈₂) significantly reduced the severity of both diseases in the com-

posted pine bark mix in which both biocontrol agents maintained high populations over 90 days. These microorganisms were less effective against damping-off in the light and dark peat mixes, respectively, in which populations of C₂₉₉R₂ declined. In contrast, crown and root rot, a disease that is severe late in the crop, was suppressed in all three types of mixes. High populations of T₃₈₂ in all three mixes late during the cropping cycle may have contributed to control of this disease.

Additional keywords: *Euphorbia pulcherrima*, natural suppression, organic amendment, organic matter decomposition, *Raphanus sativus*, *Rhizoctonia solani*.

Potting mixes may naturally suppress diseases caused by *Rhizoctonia solani* Kühn, including damping-off of radish and crown and root rot of poinsettia (24,25,40,47). Unfortunately, this suppressive effect is highly variable in nature and depends on the composition of the mixes (40,47). Differences in populations of specific biocontrol agents with activity against *R. solani* that naturally colonize the organic materials from which potting mixes are prepared seem to contribute to this variability (3,22,23,33,35,42). The microbial carrying capacity of the potting mixes, which is determined by the decomposition level of the organic matter fraction in mixes (9), also may play a role, but this factor has not been examined for diseases caused by Rhizoctonia (18,41,48).

Several biocontrol agents have been proposed as specific inoculants for potting mixes to consistently induce suppression to Rhizoctonia damping-off and reduce variability. Proposed fungal biocontrol agents include isolates of *Trichoderma* spp. (3,22,26,33,35,36,40,47), *Penicillium* spp. (25), and binucleate isolates of *R. solani* (14,27). Proposed bacterial biocontrol agents for control of Rhizoctonia diseases include *Burkholderia cepacia* (12,13), *Pseudomonas fluorescens* (2,30), *Bacillus* spp. (43), and *Streptomyces* spp. (47). Inoculants consisting of combinations of effective fungal isolates and bacterial strains, which are more effective than the single inoculants by themselves, also have been proposed. For example, Kwok et al. (34) demonstrated that *Chryseobacterium gleum* strain 299 (formerly *Flavobacterium balustinum* strain 299) and *Trichoderma hamatum* isolate 382 interact in biological control of Rhizoctonia damping-off of radish. Another approach developed for induction of suppression to Rhizoctonia damping-off in compost-amended potting mixes is to cure com-

posts after peak heating until effective indigenous biocontrol agents have naturally colonized the composts (32,48). The disadvantage of this approach is that up to 4 months may be required to induce natural suppression consistently (32).

Very little is known about the impact of the microbial carrying capacity of the organic matter used in potting mixes on the activity of biocontrol agents against Rhizoctonia diseases. Organic matter in soils or potting mixes must be fully colonized by soil microorganisms to induce microbiostasis so that *R. solani* cannot utilize this food base directly (19,20,23,37,40,42). A low concentration of cellulose added to soil improves biological control of Rhizoctonia damping-off (45). However, high concentrations of glucose present in some sources of organic matter before composting, when the concentration of cellulose also is high, not only stimulate growth of the pathogen (19,20,23,37,40,42) but also repress parasitism of *R. solani* by *Trichoderma* spp. (18,19,21). *Trichoderma* spp. reach higher populations as saprophytes in potting mixes prepared with fresh organic matter before composting when cellulose concentrations are high than in mixes prepared with mature compost in which the cellulose concentration is low and suppression is induced (16,42). During composting, the readily available sources of carbon (glucose, cellulose, etc.) are destroyed (16). Specific isolates of *Trichoderma* spp. that colonize the substrate after composting, parasitize sclerotia of *R. solani*, resulting in eradication of the pathogen and effective biological control (19).

The length of time that various sources of organic matter utilized in container media sustain these suppressive effects to diseases caused by *R. solani* remains unknown. The impact of the chemical composition of the organic matter fraction in potting mixes on the microbial carrying capacity of the mix and on microbial consortia active in biological control of Pythium damping-off was examined recently (8,28). Utilizing ¹³C cross-polarization magic angle spinning nuclear magnetic resonance and diffuse reflectance Fourier transform infrared spectroscopy, it was established that the concentrations of carbohydrates in Sphagnum peat,

Corresponding author: H. A. J. Hoitink; E-mail address: hoitink.1@osu.edu

Publication no. P-2001-0919-01R

© 2001 The American Phytopathological Society

present mostly as protected cellulose (9), and of both lignins and protected cellulose in composted sawdust-bedded cow manure (46), determine the longevity of the suppressive effect against *Pythium* damping-off and root rot. Potting mixes that are high in microbial carrying capacity become colonized naturally within days after their preparation by bacterial taxa such as *Pseudomonas* spp. and *Pantoea* spp. that provide biological control of *Pythium* damping-off and root rots (8,15). Even so, these same mixes may not become colonized naturally by the narrower spectrum of biocontrol agents capable of inducing suppression of *Rhizoctonia* damping-off until 4 months later (8,32,48). In contrast, *Arthrobacter* spp., *Micrococcus* spp., and oligotrophs, the predominant bacterial taxa in low-in-microbial-carrying-capacity, more-decomposed Sphagnum peat mixes, are consistently conducive to *Pythium* damping-off (8,9). This microflora is less active or inactive in biological control of *Pythium* damping-off (8). Similar correlations between suppressiveness and amendments with composts have been established in field soils for suppression of *Pythium* damping-off of pea (10,11), *Phytophthora* root rot of tomato (51), and some nematode diseases (38).

The objectives of this research were to determine whether the microbial carrying capacity of several sources of organic matter commonly used in potting mixes affects the efficacy of the biocontrol agent combination *C. gleum* 299 ($C_{299}R_2$) and *T. hamatum* 382 (T_{382}) in control of *Rhizoctonia* damping-off of radish and *Rhizoctonia* crown and root rot of poinsettia. An integral part of this project was the characterization of the range in suppressiveness to these diseases that occurs naturally in potting mixes prepared with sources of Sphagnum peat, demonstrated previously to differ in microbial carrying capacity, compared with in potting mixes prepared with composted pine bark.

MATERIALS AND METHODS

Potting mixes. Three types of potting mixes that previously had been shown to differ in microbial carrying capacity and in natural suppressiveness to *Pythium* damping-off and root rots were formulated as described previously (7). The first type of mix, a low-in-microbial-carrying-capacity "dark peat mix" that is naturally conducive to *Pythium* damping-off, was prepared by blending 30 different sources of dark, more decomposed H_4 on the von Post decomposition scale (44) Sphagnum peat received from Premier Peat Moss Ltd., Quebec, Canada, with coarse horticultural grade perlite (3:2, vol/vol). The second type of mix, a higher-in-microbial-carrying-capacity "light peat mix" that is naturally suppressive to *Pythium* damping-off, was prepared with 51 different sources of less decomposed H_3 on the von Post decomposition scale light Sphagnum peat received from Premier Peat Moss. Thirty additional sources of H_3 Sphagnum peat were received from Bord na Móna, Newbridge Co., Kildare, Ireland, or from Klasmann-Deilmann GmbH, Geeste-Gross Hesepe, Germany. Most were the same batches of peat as those used previously for *Pythium* bioassays (7–9). All sources of peat were stored at -15°C to avoid decomposition during storage. All H_3 peat sources were blended with coarse horticultural grade perlite as described previously for the dark peat mix. Both types of peat mixes were amended with 1.1 g of superphosphate, 1.1 g of KNO_3 , 1.1 g of gypsum, and a 3:2 ratio (wt/wt) of dolomitic lime and calcium carbonate (<100 mesh) per liter of mix to adjust the pH to within the range of 5.5 to 5.7. The third type of mix, referred hereafter as "composted pine bark mix," was prepared with dark H_4 Sphagnum peat (Premier Peat Moss), composted pine bark, medium horticultural grade vermiculite, and coarse horticultural grade perlite at ratios of 7:7:5:1 (vol/vol) according to a procedure described by Hoitink et al. (29). This mix was highest in microbial carrying capacity and suppressive to *Pythium* damping-off of cucumber (7). The following chemical additives were incorporated per liter of composted pine bark mix: 0.73 g of nitroform slow release fertilizer (38-0-0), 0.55 g of

superphosphate (0-45-0), 0.82 g of FeSO_4 (anhydrous), 0.57 g of MgSO_4 (anhydrous), 0.02 g of ZnSO_4 , 0.01 g of CuSO_4 , and 2.77 g of gypsum. The pH of this composted pine bark mix ranged from 5.5 to 5.8. The moisture content of all mixes was adjusted to approximately 50% on a total weight basis, which represents approximately 75% of the moisture content present in mixes after saturation and drainage. Autoclaved mixes were autoclaved twice for 1 h at 24-h intervals. The air capacity of all mixes after saturation with water followed by drainage in 10-cm-tall pots was >20% (vol/vol).

Inoculation of potting mixes with biocontrol agents. Eight batches of biocontrol agent-fortified mixes were prepared for each type of mix. A commercial preparation of $C_{299}R_2$ was received as a frozen paste inoculum (1.0×10^{11} CFU g^{-1}) from Chr Hansen Biosystems Inc., Milwaukee, WI. Inoculum of T_{382} was received as a granular preparation (2.0×10^8 CFU g^{-1}) from Sylvan Bio-products Inc., Cabot, PA. The biocontrol agents were blended separately into potting mixes during preparation of the mix to theoretical inoculum densities of 2.0×10^6 CFU g^{-1} dry weight mix for $C_{299}R_2$ and 1.0×10^5 CFU g^{-1} dry weight mix for T_{382} . Control mixes were made with the same materials but were not fortified with $C_{299}R_2$ or T_{382} . These mixes, which are colonized by indigenous microorganisms, are hereafter referred to as natural dark peat, natural light peat, and natural composted pine bark mixes.

The population of $C_{299}R_2$ in potting mixes not inoculated with the pathogen was determined by tracking a spontaneous rifampicin-resistant mutant ($C_{299}R_2$) on a selective medium containing 0.1 g of rifampicin per liter of medium (34). The minimal detectable population of $C_{299}R_2$ in the potting mixes on this medium was 10^3 CFU g^{-1} dry weight mix. The yellow-pigmented colony morphology of this biocontrol agent allowed it to be easily separated from colonies of other microorganisms on this medium. The identity of strains recovered from these colonies was confirmed further by gas chromatographic fatty acid methyl-esters (GC-FAME) analysis (MIDI Library version 3.6; Microbial ID Inc., Newark, DE). The branched unsaturated fatty acid i17:1 ω 8 is the most prominent fatty acid produced by C_{299} (including $C_{299}R_2$) and is unique among rhizosphere microorganisms in potting mixes (49).

The population of T_{382} in potting mixes not inoculated with the pathogen was determined as described previously for $C_{299}R_2$ but by dilution plating on a *Trichoderma*-selective medium (17). Phialides produced by *T. hamatum* were examined under a dissecting microscope at $\times 200$ (5). A specific random amplified polymorphic DNA (RAPD) marker developed by Abbasi et al. (1) was used to verify the identity of T_{382} . This procedure was applied to DNA extracted from cultures of three colonies randomly selected from each dilution plate on which colonies were counted.

Immediately after formulation of the biocontrol agent-fortified and natural (control) potting mixes and at approximately 14-day intervals for 90 days thereafter, 10 g (wet weight) of a mix was suspended in 90 ml of 0.1% sterilized water agar (three replicates per sample). Dilution plates were then made in triplicate on the selective media ($n = 9$). Colonies of $C_{299}R_2$ and T_{382} were counted after 4 and 10 days of incubation at 25°C , respectively. The identity of three presumed T_{382} colonies per sample was verified by polymerase chain reaction (PCR). Populations of both organisms were not always monitored on the same day because of the large amount of time required for verification of biocontrol agent identities for each procedure.

Rhizoctonia damping-off of radish bioassay. The potential for suppression of *Rhizoctonia* damping-off in the three potting mixes was determined according to Kwok et al. (34) with a radish (*Raphanus sativus* L.) bioassay, utilizing cv. Early Scarlet Globe (85% germination). Isolate 19 of *R. solani*, an anastomosis group 4 (AG-4) mating type originally isolated from poinsettia in the C. Wayne Ellett Plant and Pest Diagnostic Clinic at The Ohio State

University, was used in this bioassay. Soil inoculum of *R. solani* was prepared in chopped potato soil as described by Ko and Hora (31). Wooster silt loam was used as soil in this medium. Air dried soil inoculum was ground with a mortar and pestle and screened to collect 1- to 2-mm particles as described by Nelson and Hoitink (40). Potting mixes were then infested with 0.5 g of this screened soil inoculum per liter of mix prior to potting. This bioassay was made slightly more sensitive than the previous bioassay (40) by increasing the rating scale from four to five disease severity categories. This assay allows for consistent separation of strongly suppressive mixes from those conducive to Rhizoctonia damping-off. Slow release fertilizer (Osmocote 17-6-12 Plus Minors; The Scotts Company, Marysville, OH) was incorporated into each mix (13.5 g/liter).

Radish seeds (32 per pot) were planted with a pneumatic seeder at a mean distance of 1.4 cm from one another in 10-cm-diameter polystyrene foam pots containing approximately 400 cm³ of potting mix as described previously (41). Pots were watered and incubated in growth chambers at 24 to 25°C under 24-h illumination (225 microeinsteins m⁻² s⁻¹). Damping-off severity was determined 7 days after seeding based on a disease severity scale in which 1 = symptomless; 2 = small root or stem lesion but not damped-off; 3 = large root or stem lesion but not damped-off; 4 = postemergence damping-off; and 5 = preemergence damping-off. Identity of the pathogen was confirmed by its isolation on acidified potato dextrose agar (APDA; Becton Dickinson, Sparks, MD) followed by examination with light microscopy. All radish bioassays were configured according to a randomized complete block design. Each treatment was replicated five times (five pots of 32 seeds per treatment).

Severity of Rhizoctonia damping-off of radish in natural and biocontrol agent-fortified potting mixes. The suppressiveness of natural potting mixes (i.e., not fortified with biocontrol agents) to Rhizoctonia damping-off was evaluated immediately after their preparation based on the mean damping-off severity and the proportion of severely diseased seedlings (disease severity values >2) observed in infested mixes. A total of 30 natural batches of dark peat mix, 81 natural batches of light peat mix, and 71 natural batches of composted pine bark mix were tested with the radish bioassay. Analysis of variance (ANOVA) was used to determine the effects of potting mix batch and potting mix treatment on damping-off severity. The mix treatment factors included

potting mix type (dark peat, light peat, and composted pine bark), addition of *R. solani* inoculum, and autoclaving. Batch was considered a random effect and treatment a fixed effect in the ANOVA model. Two aspects of damping-off severity were analyzed as the response variables. The disease rating for each replication (*R*), which ranged from 1 to 5, was transformed to $R^* = (R^{1.5} - 1)/1.5$ to obtain a linear scale and an approximately normally distributed variable with constant variance. The second response variable was the proportion of seedlings in each replication with damping-off severity ratings >2 (*y*) (i.e., the proportion of severely diseased seedlings). This was transformed to $y^* = \arcsine(\sqrt{y})$ to obtain a constant variance. The general linear models (GLM) procedure of SAS (version 8; SAS Institute, Cary, NC) was used to conduct the analysis. When a factor was significant, the least significant difference (LSD) at *P* = 0.05 was calculated to compare means of transformed data (R^* , y^*).

To determine the efficacy of the biocontrol agents against Rhizoctonia damping-off, radish bioassays were performed on eight different batches of natural or biocontrol agent-fortified dark peat mix, light peat mix, and composted pine bark-amended mix as described above. These bioassays were performed immediately after the potting mixes were prepared and inoculated with the biocontrol agents. ANOVA was used to determine the effects of potting mix batch, mix treatment, biocontrol agent fortification, and their interactions on damping-off severity. As described previously, the transformed rating (R^*) and the transformed proportion of plants in each replication with a rating >2 (y^*) were analyzed as the response variables. Batch was considered a random factor, and mix treatment and biocontrol agent fortification were considered fixed factors. An LSD was calculated when a factor or interaction was significant (*P* = 0.05) to compare means of the transformed data.

Rhizoctonia crown and root rot of poinsettia bioassay. The potential for suppression of Rhizoctonia crown and root rot of poinsettia (*Euphorbia pulcherrima* Willd.) in the three types of potting mixes fortified with the biocontrol agents C₂₉₉ and T₃₈₂ was evaluated immediately after formulation of the mixes by comparing disease severity data in the natural and the biocontrol agent-fortified mixes, as described above under Rhizoctonia damping-off of radish. Rooted cuttings of poinsettia (cv. Freedom Red), received from Paul Ecke Ranch, Encinitas, CA, rooted in Oasis blocks (Smithers-Oasis, Kent, OH), were planted in 1.2-liter

TABLE 1. Severity of Rhizoctonia damping-off of radish (*Raphanus sativus* L. 'Early Scarlet Globe') among numerous batches of dark peat, light peat, and composted pine bark-amended potting mixes

Potting mix ^a	<i>Rhizoctonia solani</i> inoculum ^b	Rhizoctonia damping-off severity ^c				Number of batches tested
		Mean rating (<i>R</i>) ^d	Transformed mean rating (R^*) ^e	Mean proportion >2 (<i>y</i>) ^f	Mean transformed proportion >2 (y^*) ^g	
Dark peat	—	1.2	0.19	0.04	0.16	30
Dark peat	+	3.8	4.27	0.80	1.16	30
Autoclaved dark peat	+	4.1	4.84	0.82	1.16	13
Light peat	—	1.1	0.16	0.04	0.14	13
Light peat	+	4.1	4.99	0.88	1.29	81
Autoclaved light peat	+	3.9	4.55	0.80	1.14	13
Composted pine bark	—	1.2	0.22	0.05	0.19	13
Composted pine bark	+	3.4	3.68	0.67	0.99	71
Autoclaved composted pine bark	+	3.4	3.55	0.65	0.95	13
LSD _{0.05} ^h	...	...	0.45	...	0.08	...

^a Autoclaved mixes were autoclaved twice for 1 h at 24-h intervals prior to planting.

^b + = potting mixes infested with 0.5 g of soil inoculum of *R. solani* isolate 19 per liter of mix; and — = not infested.

^c Mean damping-off severity determined 7 days after planting. Rating based on five pots of 32 plants each and a damping-off severity scale in which 1 = symptomless; 2 = small root or stem lesion; 3 = large root or stem lesion; 4 = postemergence damping-off; and 5 = preemergence damping-off.

^d Mean damping-off severity for all batches of a mix (*R*).

^e Disease rating for each replication (*R*) was transformed to $R^* = (R^{1.5} - 1)/1.5$ in order to obtain a linear scale and an approximately normally distributed variable with constant variance. Analysis of variance (ANOVA) and least significant difference (LSD) were based on R^* (not *R*) and y^* (not *y*).

^f Mean proportion of plants in each replication with a disease severity rating >2 (*y*).

^g Mean proportion of plants in each replication with a disease severity rating of >2 (*y*) was transformed to $y^* = \arcsine(\sqrt{y})$ to obtain a constant variance.

^h Differences in R^* and y^* larger than the LSD (within columns) are significantly different (*P* = 0.05). Because ANOVA was performed on transformed data, an LSD cannot be calculated for *R* and *y*.

(15-cm-diameter) plastic pots (one plant per pot). Soil inoculum of *R. solani* isolate 3, an AG-4 mating type (received from D. M. Benson, North Carolina State University, Raleigh), was prepared as described above for isolate 19 of *R. solani*. The inoculum was applied to the surface of the mix in each pot (40 mg at two opposing locations at 5 cm from the stem) immediately after planting of the crop according to Benson (4). This inoculum was then covered with approximately 1 cm of the same potting mix. Unless specified otherwise, the following treatments were used in this bioassay for each potting mix type: natural (not fortified with biocontrol agents) and biocontrol agent-fortified mixes; pathogen-infested and noninfested control mixes; autoclaved pathogen infested; and a fungicide-drenched pathogen-infested control. A fungicide drench recommended for poinsettia (39) containing thiophanate methyl (0.68 mg a.i. ml⁻¹ water) and metalaxyl (0.02 mg a.i. ml⁻¹) was applied immediately after potting and monthly thereafter (125 ml of solution per pot).

Plants were grown in a greenhouse at a temperature range of 17 to 25°C with naturally occurring photoperiods. Fertilizer (200 mg/liter of Peters 20-20-20 Poinsettia Fertilizer, The Scotts Company) was applied twice per week. Plants were harvested after 6 to 8 weeks, depending upon seasonal impacts on crop development for each bioassay, and rated for crown and root rot severity based on a scale in which 1 = symptomless; 2 = mild root rot; 3 = mild crown rot; 4 = severe crown rot; and 5 = dead plant. Identity of the pathogen was verified by plating of affected root or stem tissue on APDA followed by examination with light microscopy.

A randomized complete block design was used in each poinsettia bioassay. Three replicates of three plants each were used per treatment in the first bioassay. Because of differences in availability of rooted cuttings, the number of plants per replicate as well as the number of replicates per treatment was adjusted to two replicates of four and three replicates of four plants per treatment in the second and third bioassays, respectively. ANOVA was used to determine the effects of potting mix treatment (includes mix type, addition of *R. solani* inoculum or biocontrol agent, and fungicide), bioassay, and the interaction of bioassay and mix treatment on transformed disease severity rating (R^*). Bioassay

was considered a random effect and mix treatment a fixed effect. An LSD was calculated when a factor or interaction was significant ($P = 0.05$) in order to compare means of transformed data. The number of poinsettia plants in each replication was insufficient to precisely estimate the proportion of plants with a rating greater than 2 (y). However, the number of plants was sufficient to analyze mean disease severity ratings.

RESULTS

Severity of damping-off of radish in natural potting mixes.

The severity of Rhizoctonia damping-off on radish seedlings grown in several batches of natural dark peat mix, light peat mix, and composted pine bark mix is summarized in Table 1. ANOVA indicated that potting mix batch did not significantly affect either transformed mean disease severity (R^*) or the transformed proportion of plants with a disease severity rating >2 (y^*) ($P > 0.20$). Potting mix treatment (e.g., mix type) had a significant effect ($P < 0.01$) on R^* and y^* , indicating that mix type (e.g., dark peat) or how it was treated (e.g., autoclaved, inoculated with the pathogen) affected disease severity. The following specific observations were made: The mean damping-off severity observed on radish seedlings in 30 batches of infested natural dark peat mixes was 3.8. The mean damping-off severity in 81 batches of infested natural light peat mixes (4.1) was significantly higher than that in the dark peat mixes based on the LSD ($P = 0.05$). Finally, the mean damping-off severity observed in 71 batches of infested natural composted pine bark mixes (3.4) was significantly lower than that observed in either type of infested natural peat mixes.

The mean proportion of severely diseased seedlings in the infested natural dark peat mixes was 0.80 (Table 1). In the infested natural light peat mixes, this proportion was significantly higher (0.88). In contrast, the proportion of severely diseased seedlings in the infested natural composted pine bark mixes was only 0.67. Autoclaving slightly increased the damping-off severity in the infested natural dark peat mixes, but decreased the severity in the light peat mixes. Autoclaving did not have a significant effect in the composted pine bark mixes based on the LSD ($P = 0.05$).

TABLE 2. Efficacy of the biocontrol agents *Chryseobacterium gleum* 299R₂ and *Trichoderma hamatum* 382 in suppression of Rhizoctonia damping-off of radish (*Raphanus sativus* L. 'Early Scarlet Globe') in eight different batches of fortified and natural dark peat, light peat, and composted pine bark-amended potting mixes

Potting mix ^a	<i>Rhizoctonia solani</i> inoculum ^b	Rhizoctonia damping-off severity ^c							
		Mean rating (R) ^d		Transformed mean rating (R^*) ^e		Mean proportion >2 (y) ^f		Mean transformed proportion >2 (y^*) ^g	
		Natural mix	Biocontrol fortified mix	Natural mix	Biocontrol fortified mix	Natural mix	Biocontrol fortified mix	Natural mix	Biocontrol fortified mix
Dark peat	–	1.2	1.3	0.28	0.40	0.06	0.09	0.20	0.26
Dark peat	+	3.6	3.7	4.05	4.07	0.80	0.75	1.15	1.08
Autoclaved dark peat	+	3.7	3.9	4.27	4.62	0.74	0.80	1.07	1.14
Light peat	–	1.2	1.3	0.25	0.41	0.06	0.09	0.20	0.26
Light peat	+	3.8	3.2	4.47	3.16	0.84	0.63	1.20	0.94
Autoclaved light peat	+	3.7	3.8	4.02	4.37	0.71	0.74	1.01	1.07
Composted pine bark	–	1.2	1.2	0.22	0.17	0.05	0.04	0.17	0.16
Composted pine bark	+	3.4	2.2	3.58	1.60	0.67	0.36	0.99	0.64
Autoclaved composted pine bark	+	3.5	3.2	3.74	3.21	0.66	0.61	0.96	0.91
LSD _{0.05} ^h				0.85				0.16	

^a Autoclaved mixes were autoclaved twice for 1 h at 24-h intervals prior to planting.

^b + = potting mixes infested with 0.5 g of soil inoculum of *R. solani* isolate 19 per liter of mix; and – = not infested.

^c Mean damping-off severity determined 7 days after planting. Rating based on five pots of 32 plants each and a damping-off severity scale in which 1 = symptomless; 2 = small root or stem lesion; 3 = large root or stem lesion; 4 = postemergence damping-off; and 5 = preemergence damping-off.

^d Mean damping-off severity for all batches of a mix.

^e Disease rating for each replication (R) was transformed to $R^* = (R^{1.5} - 1)/1.5$ in order to obtain a linear scale and an approximately normally distributed variable with constant variance.

^f Mean proportion of plants in each replication with a disease severity rating of >2 .

^g Mean proportion of plants in each replication with a disease severity rating of >2 (y) was transformed to $y^* = \arcsin(\sqrt{y})$ to obtain a constant variance.

^h Differences in R^* and y^* larger than the LSD (within or across respective columns) are significantly different ($P = 0.05$). Because analysis of variance was performed on transformed data, an LSD cannot be calculated for R and y .

Autoclaving did not significantly affect the proportion of severely diseased seedlings in the infested natural dark peat and composted pine bark mixes, but significantly reduced this proportion in the infested natural light peat mixes. Disease severity values in non-infested control mixes were consistently low. *R. solani* was recovered on APDA from diseased seedlings. In conclusion, the mean damping-off severity in all infested natural mixes was very high, but the lowest values were observed in the infested natural composted pine bark mixes.

Severity of damping-off of radish in potting mixes fortified with C₂₉₉R₂ and T₃₈₂. The effects of the biocontrol agents on the severity of damping-off in eight different infested batches of the three different types of potting mixes are summarized in Table 2. Based on ANOVA, there was no significant effect of potting mix batch on either the transformed disease rating (*R*^{*}) or the transformed proportion (*y*^{*}) of plants with a rating >2 (*P* > 0.20). Lack of significance indicated that the source of the potting mix, in general, did not affect the results. Potting mix treatment, biocontrol-agent fortification, and their interaction all significantly affected *R*^{*} and *y*^{*} (*P* < 0.05). The interaction indicated that differences among some mix treatments depended on whether the biocontrol agents were added or the effect of the biocontrol agents depended on a specific mix treatment. The following specific observations were made: The severity of Rhizoctonia damping-off on radish plants in all eight batches of the three types of infested natural mixes was high, as also shown for these mixes in Table 1. The mean proportions of severely diseased seedlings in the infested natural dark peat and light peat mixes were 0.80 and 0.88, respectively. The mean proportion of affected seedlings in the infested composted pine bark mixes was low (0.67), as was also shown in the results for bioassays in Table 1.

Inoculation of the infested dark peat mixes with the biocontrol agents C₂₉₉R₂ and T₃₈₂ did not significantly decrease the severity of damping-off in the eight batches of this mix (Table 2) as determined by the LSD for interaction of means (*P* = 0.05). Autoclaving did not significantly affect the damping-off severity rating of seedlings in this biocontrol agent-fortified dark peat mix

either. Inoculation of the infested light peat mixes with C₂₉₉R₂ and T₃₈₂ significantly decreased the severity of damping-off from a mean value of 3.8 in the infested natural to 3.2 in the infested biocontrol agent-fortified light peat mixes. Autoclaving eliminated this suppressive effect. Inoculation of the infested composted pine bark mixes with C₂₉₉R₂ and T₃₈₂ had a large and significant effect on the severity of damping-off of radish seedlings. The mean disease severity value was reduced from 3.4 in the infested natural to 2.2 in the infested biocontrol agent-fortified composted pine bark mixes, and autoclaving destroyed this suppressive effect. Even so, the severity of the disease in these autoclaved composted pine bark mixes still was significantly lower than that observed in infested autoclaved light peat or dark peat mixes. The mean damping-off severity of seedlings in the infested biocontrol agent-fortified light peat mixes (3.2) was significantly lower than that observed in the infested biocontrol agent-fortified dark peat mixes (3.7). By far, the lowest mean severity value (2.2) was observed on seedlings in the infested biocontrol agent-fortified composted pine bark mixes.

The mean transformed proportion of severely diseased seedlings in the infested dark peat mixes was not affected significantly by inoculation with C₂₉₉R₂ and T₃₈₂, based on the interaction LSD (*P* = 0.05). The proportion of severely diseased seedlings in the infested biocontrol agent-fortified light peat mixes was reduced significantly from 0.84 to 0.63. C₂₉₉R₂ and T₃₈₂ were even more effective in the composted pine bark mixes in which the proportion of seedlings with severe symptoms was reduced from 0.67 to 0.36. A comparison of the transformed proportions of severely diseased seedlings among the three types of potting mixes inoculated with C₂₉₉R₂ and T₃₈₂ revealed that values for the dark and light peat mixes did not differ significantly, but that this proportion in the infested biocontrol agent-fortified composted pine bark mixes was significantly lower than the proportion in either type of the infested biocontrol agent-fortified peat mixes. In summary, based on mean damping-off severity values as well as the proportion of severely diseased seedlings, the biocontrol agents C₂₉₉R₂ and T₃₈₂ had a significant effect on the severity of Rhizoctonia

TABLE 3. Efficacy of the biocontrol agents *Chryseobacterium gleum* 299R₂ and *Trichoderma hamatum* 382, and the fungicides metalaxyl and thiophanate-methyl in control of Rhizoctonia crown and root rot of poinsettia (*Euphorbia pulcherrima* Willd. 'Freedom Red') in three different batches of dark peat, light peat, and composted pine bark-amended potting mixes

Potting mix	Biocontrol inoculum ^a	<i>Rhizoctonia solani</i> inoculum ^b	Fungicide drench ^c	Rhizoctonia crown and root rot severity ^d					
				Bioassay I		Bioassay II		Bioassay III	
				Mean rating (<i>R</i>) ^e	Transformed mean rating (<i>R</i> [*]) ^f	Mean rating (<i>R</i>)	Transformed mean rating (<i>R</i> [*])	Mean rating (<i>R</i>)	Transformed mean rating (<i>R</i> [*])
Dark peat	–	–	–	1.0	0	1.0	0	1.0	0
Dark peat	–	+	–	3.9	4.53	3.3	3.53	2.4	2.31
Dark peat	+	+	–	1.6	0.89	2.9	2.87	1.9	1.31
Dark peat	–	+	+	1.9	1.11	2.5	2.25	1.6	0.83
Light peat	–	–	–	1.0	0	1.0	0	1.0	0
Light peat	–	+	–	3.3	3.47	3.4	3.68	2.9	2.83
Light peat	+	+	–	1.6	0.85	2.5	2.25	1.7	1.04
Light peat	–	+	+	1.8	1.17	1.1	0.15	1.0	0
Composted pine bark	–	–	–	1.1	0.15	1.3	0.30	1.1	0.14
Composted pine bark	–	+	–	2.8	2.44	2.8	2.51	4.1	4.93
Composted pine bark	+	+	–	2.0	1.39	2.8	2.71	1.2	0.27
Composted pine bark	–	+	+	1.5	0.65	1.8	0.91	1.5	0.61
LSD _{0.05} (transformed mean rating) ^g							1.25		

^a + = *C. gleum* 299 and *T. hamatum* 382 inoculated during mix formulation into potting mixes at initial inoculum densities of 2.0×10^6 and 1.0×10^5 CFU g⁻¹ dry weight mix, respectively; and – = no inoculum.

^b + = potting mixes infested with 0.5 g of soil inoculum of *R. solani* isolate 3 per liter of mix; and – = not infested.

^c Fungicide drench (thiophanate methyl and metalaxyl) was applied monthly at the recommended rate.

^d Crown and root rot severity determined 42 to 60 days after planting based on a scale in which 1 = symptomless; 2 = mild root rot; 3 = mild root and crown rot; 4 = severe root and crown rot; and 5 = dead plant.

^e Mean disease severity (*R*).

^f Disease rating for each replication in each bioassay (*R*) was transformed to $R^* = (R^{1.5} - 1)/1.5$ in order to obtain a linear scale and an approximately normally distributed variable with constant variance. Analysis of variance (ANOVA) and least significant difference (LSD) were based on *R*^{*} (not *R*).

^g Differences of *R*^{*} larger than LSD (within or across columns) are significantly different (*P* = 0.05). Because ANOVA was performed on transformed data, an LSD cannot be calculated for *R* and *y*.

damping-off of radish in the infested composted pine bark mixes. They were less effective in the light peat mixes and not effective in the dark peat mixes.

Effect of $C_{299}R_2$ and T_{382} on the severity of Rhizoctonia crown and root rot of poinsettia. The effects of $C_{299}R_2$ and T_{382} on the severity of Rhizoctonia crown and root rot of poinsettia in three different batches of each of the three types of potting mixes are presented in Table 3. ANOVA indicated that there was no overall effect of bioassay on the transformed disease severity rating (R^*) ($P > 0.20$). However, potting mix treatment and the interaction of mix treatment and bioassay significantly affected disease severity ($P < 0.01$). This interaction indicated that the differences in R^* between mix treatments varied with the bioassay. Most plants in the natural mixes infested with *R. solani* developed stem rot lesions within 18 days after planting. Severe crown and root rot developed later on these plants during production of the crop and few remained symptomless. Plants died within 14 days after potting in autoclaved infested mixes (data not shown). The plants produced in mixes not infested with *R. solani* did not develop symptoms of the disease.

In the first bioassay, inoculation of the dark peat and light peat mixes with $C_{299}R_2$ and T_{382} significantly reduced the severity of crown and root rot (Table 3) based on the interaction LSD ($P = 0.05$). For instance, mean severity in the natural light peat mix was reduced from 3.3 to 1.6 by fortifying with $C_{299}R_2$ and T_{382} . In the biocontrol agent-fortified composted pine bark mix, the suppressive effect was less apparent, probably because the severity of the disease in that natural batch of infested composted pine bark mix (2.8) was much lower than in either type of infested natural peat mix. In all three types of mixes, the efficacy of the biocontrol agents did not differ significantly from that provided by monthly drenches of natural mixes with thiophanate-methyl and metalaxyl.

In the second bioassay, the severity of the disease in the natural dark peat mix was high and the biocontrol agents $C_{299}R_2$ and T_{382} did not significantly reduce disease severity (Table 3). However, the biocontrol agents did have a significant effect in the natural light peat mix. Finally, they did not have a significant effect in the composted pine bark mix but the severity of the disease in that batch of natural mix was low compared with other bioassays. The fungicide drenches significantly suppressed the severity of crown and root rot on plants in all three potting mixes.

In the third bioassay, crown and root rot was most severe on plants grown in the infested natural composted pine bark mix, revealing that it was highly conducive in this bioassay. Fortification with the biocontrol agents had a large and significant effect on disease severity in that batch of composted pine bark mix (mean severity value of 4.1 reduced to 1.2). The degree of suppression of the disease obtained with the biocontrol agents in this batch of mix did not differ from that obtained with monthly drenches with thiophanate-methyl and metalaxyl. In this bioassay, the mean disease severity values in the natural dark and light peat mixes were low (2.3 and 2.9, respectively). The biocontrol agents did not further reduce the severity of the disease in the dark peat mix but they did have a slight but significant effect in the light peat mix. Efficacy of the biocontrol agents in the light peat mix did not differ significantly from that provided by the fungicide drenches.

In conclusion, the biocontrol agents were most effective in those mixes where the severity of Rhizoctonia crown and root rot in the infested natural mix was highest (bioassays I and III). This was observed irrespective of the potting mix type. Finally, significant effects due to inoculation with biocontrol agents were not observed when disease severity values in the infested natural potting mixes were very low, suggesting that they had already been colonized naturally by effective indigenous microorganisms. (bioassay II).

Populations of $C_{299}R_2$ and T_{382} in potting mixes. Figure 1 illustrates population densities of $C_{299}R_2$ and T_{382} in the potting

mixes not inoculated with the pathogen used in the first Rhizoctonia crown and root rot of poinsettia bioassay. The population of $C_{299}R_2$ in the light and dark peat mixes declined from 5.0×10^6 and 2.5×10^6 CFU g^{-1} dry weight mix, respectively, immediately after potting to $<10^5$ CFU g^{-1} dry weight mix at 70 days after potting (Fig. 1A). In contrast, the population of $C_{299}R_2$ in the composted pine bark mix did not decline significantly during the first 60 days after potting and it remained above 2.5×10^5 CFU g^{-1} dry weight thereafter. Similar population trends were observed in the other bioassays. $C_{299}R_2$ consistently was not recovered from control mixes (data not shown).

The population of T_{382} in the composted pine bark mix consistently remained $\geq 10^5$ CFU g^{-1} dry weight mix through 90 days after potting in all batches tested. In contrast, a significant decline in population was consistently observed soon after planting in both peat mixes. Figure 1B (bioassay I) reveals a decline in populations of T_{382} in the peat mixes within hours after potting.

The population of T_{382} increased with time thereafter in both peat mixes until it was not significantly ($P = 0.05$) different from that in the composted pine bark mix after 70 days. T_{382} was not recovered from control mixes not inoculated with this biocontrol agent.

DISCUSSION

This work revealed that the severity of Rhizoctonia damping-off of radish seedlings grown in natural potting mixes that were colonized by indigenous microorganisms and infested with the pathogen was very high, regardless of the microbial carrying capacity

Fig. 1. Mean population densities ($\pm$ standard errors) of **A**, *Chryseobacterium gleum* 299R₂ and **B**, *Trichoderma hamatum* 382 during production of a poinsettia crop in dark peat (□), light peat (Δ), and composted pine bark potting mixes (○).

of the mix (Table 1). The mean proportions of severely diseased seedlings in the dark and light peat and composted pine bark mixes were 0.80, 0.88, and 0.67, respectively (Table 1). Even though potting mixes prepared with light Sphagnum peat harvested from near the surface of bogs (47) or with any of several types of composts may suppress this disease (24,25,32,33,41,48), the degree of natural suppression detected in this work was very low and commercially unacceptable. Thus, the microbial carrying capacity of the three types of mixes used in this work was not predictive of suppressiveness to *Rhizoctonia* damping-off of radish as reported previously for suppressiveness to *Pythium* damping-off of cucumber and *Pythium* root rot of poinsettia (7). Approximately 50 of the 81 batches of light peat mixes used in this work (Table 1) were the same as those reported to be suppressive to *Pythium* damping-off by Boehm (6). Because autoclaving destroyed the suppressive effects against both types of damping-off diseases (Table 2 and Boehm [6]), this difference in natural suppressiveness to *Pythium* and *Rhizoctonia* damping-off is perhaps best explained by differences in the spectrum of indigenous microorganisms that effectively suppress these two types of diseases. Boehm et al. (8,9) demonstrated that a great diversity of indigenous biocontrol agents in the high-in-microbial-carrying-capacity composted pine bark mixes and light peat mixes can contribute to control of *Pythium* damping-off in these mixes. Apparently, such microorganisms with efficacy against *Rhizoctonia* damping-off did not consistently colonize the 182 different batches of potting mixes used in this work. Even so, the natural composted pine bark mixes were more frequently suppressive than the peat mixes.

Inoculation of the three types of potting mixes with the biocontrol agents $C_{299}R_2$ and T_{382} did provide some evidence that the microbial carrying capacity of the mixes affected efficacy of these biocontrol agents against *Rhizoctonia* damping-off (Table 2). They were highly effective in the high-in-microbial-carrying-capacity composted pine bark mixes, where a mean damping-off severity of 2.2 was observed in the inoculated mixes. The introduced biocontrol agents were less effective in the light peat mixes (mean damping-off severity of 3.2) and had no effect in the dark peat mixes (mean damping-off severity of 3.7), which were lowest in microbial carrying capacity (8). We conclude, therefore, that the decomposition level of Sphagnum peat, based on the von Post decomposition scale (44), seems to have a slight effect on the efficacy of these and possibly other biocontrol agents used for control of *Rhizoctonia* damping-off in potting mixes. It is clear, however, that they were much more effective in the composted pine bark mix.

Trends in efficacy of $C_{299}R_2$ and T_{382} in the three types of potting mixes for control of *Rhizoctonia* crown and root rot of poinsettia share similarities with those discussed above for control of *Rhizoctonia* damping-off of radish. In two of the three bioassays (Table 3), the degree of control provided by $C_{299}R_2$ and T_{382} in the fortified composted pine bark mixes did not differ significantly from that obtained with monthly fungicide drenches. Although the biocontrol agents had a significant effect in the highly conducive batch of composted pine bark mix (bioassay III) and in each bioassay in the light peat mixes, they were only effective in one of the two conducive batches of dark peat mixes. The foregoing suggests that the microbial carrying capacity of these potting mixes did have some but not a critical effect on the control of this disease on poinsettia, whereas it clearly has such a predictive effect in control of *Pythium* root rot of this crop in these same types of mixes (7).

Differences in the efficacy of the biocontrol agents observed in suppression of *Rhizoctonia* damping-off of radish versus that of *Rhizoctonia* crown and root rot of poinsettia may possibly be explained on the basis of pathogen inoculum distribution in the mix and susceptibility of the host. *R. solani* is an aggressive pathogen of seedlings of many plant species (4,23). In the damping-off bioassay used in this work, the inoculum of the pathogen was dis-

tributed evenly throughout the potting mixes among radish seeds planted at uniform distances (41). Most of the visible disease symptoms developed within the first 4 days after potting, and the biocontrol agents would need to be highly effective immediately after potting to provide control. Effective control of this disease was only observed in the biocontrol agent-fortified high-in-microbial-carrying-capacity composted pine bark mixes. In the longer term poinsettia bioassay, care was taken to place the inoculum at a distance of 5 cm from the stem to avoid stem rot. Because root rot did not develop until several weeks after potting in this bioassay in all but the autoclaved mixes, ample opportunity existed for long-term interactions between the biocontrol agents and *R. solani*. $C_{299}R_2$ may have contributed to biological control of both diseases in the biocontrol agent-fortified composted pine bark-amended mix because it maintained high populations throughout the 90-day test period. This agrees with earlier observations for this biocontrol agent in composted hardwood bark mixes (34). In the peat mixes, however, its population declined rapidly after 30 days. This suggests that $C_{299}R_2$ contributed very little to the control of *Rhizoctonia* crown and root rot of poinsettia because its population late in the production cycle of this crop was low ($<10^5$ CFU g^{-1} dry weight mix) when the disease was most severe. This low population of $C_{299}R_2$ is well below that required for effective control obtained with bacterial biocontrol agents in general (50).

Trends in populations of *T. hamatum* 382 (confirmed by RAPD analysis) perhaps best explain the degree of control observed for *Rhizoctonia* crown and root rot of poinsettia in the three potting mixes. Its population early after potting ranged between 10^5 and 10^6 CFU g^{-1} dry weight mix, which is within the range published for composted hardwood bark-amended potting mixes suppressive to *Rhizoctonia* damping-off (17,34,41). In both peat mixes, however, where *Rhizoctonia* damping-off was not controlled effectively (Table 2), the population of T_{382} declined soon after potting. This may have been due to lysis of the conidial inoculum of T_{382} introduced as commercial inoculum into these lower-in-microbial-carrying-capacity peat mixes. The population of T_{382} increased later (Fig. 1B) in the peat mixes when symptoms of *Rhizoctonia* crown and root rot also were most severe in mixes infested with *R. solani* that were not fortified with the biocontrol agents (Table 3). In conclusion, only the biocontrol agent-fortified, highest-in-microbial-carrying-capacity composted pine bark mix, which supported high populations of both biocontrol agents, suppressed both types of *Rhizoctonia* diseases consistently.

ACKNOWLEDGMENTS

This research was supported by grants from USDA-IR-4 (Cook College, Rutgers University, New Brunswick, NJ), The Ohio Floriculture Foundation (Columbus, OH), and Gustafson Inc. (Dallas, TX). Salaries and research support were provided by State and Federal Funds to The Ohio Agricultural Research and Development Center, The Ohio State University. We thank the Paul Ecke Ranch (Encinitas, CA) for providing rooted poinsettia cuttings, C. A. Musselman for providing technical assistance, and M. J. Boehm for critical review of the manuscript.

LITERATURE CITED

1. Abbasi, P. A., Miller, S. A., Meulia, T., Hoitink, H. A. J., and Kim, J.-M. 1999. Precise detection and tracing of *Trichoderma hamatum* 382 in compost-amended potting mixes using molecular markers. *Appl. Environ. Microbiol.* 65:5421-5426.
2. Bagnasco, P., de la Fuente, L., Gualtieri, G., Noya, F., and Arias, A. 1998. Fluorescent *Pseudomonas* spp. as biocontrol agents against forage legume root pathogenic fungi. *Soil Biol. Biochem.* 30:1317-1322.
3. Baker, R. 1987. Mycoparasitism: Ecology and physiology. *Can. J. Plant Pathol.* 9:370-379.
4. Benson, D. M. 1991. Control of *Rhizoctonia* stem rot of poinsettia during propagation with fungicides that prevent colonization of rooting cubes by *Rhizoctonia solani*. *Plant Dis.* 75:394-398.
5. Bissett, J. 1991. A revision of the genus *Trichoderma*. II. Infrageneric

- classification. Can. J. Bot. 69:2357-2372.
6. Boehm, M. J. 1992. Microbial ecology of Canadian Sphagnum peat and compost-amended potting mixes varying in suppressiveness to Pythium root rot and damping-off. Ph.D. diss. The Ohio State University, Columbus.
7. Boehm, M. J., and Hoitink, H. A. J. 1992. Sustenance of microbial activity in potting mixes and its impact on severity of Pythium root rot of poinsettia. Phytopathology 82:259-264.
8. Boehm, M. J., Madden, L. V., and Hoitink, H. A. J. 1993. Effect of organic matter decomposition level on bacterial species diversity and composition in relation to Pythium damping-off severity. Appl. Environ. Microbiol. 59:4171-4179.
9. Boehm, M. J., Wu, T., Stone, A. G., Kraakman, B., Iannotti, D. A., Wilson, G. E., Madden, L. V., and Hoitink, H. A. J. 1997. Cross-polarized magic-angle spinning ¹³C nuclear magnetic resonance spectroscopic characterization of soil organic matter relative to culturable bacterial species composition and sustained biological control of Pythium root rot. Appl. Environ. Microbiol. 63:162-168.
10. Brüns, C. 1996. Suppressiv Effekte von Komposten aus der getrennten Sammlung organischer Abfälle und von Rindermistkompost gegenüber rodenbürtigen Schaderegern. Ph.D. diss. University of Kassel, Germany.
11. Brüns, C., Ahlers, S., Gättinger, A., Schüler, C., Vogtmann, H., and Wolf, G. 1996. The suppressive effects of composted separately collected organic waste and yard waste compost on two important soilborne plant pathogens. Pages 1094-1095 in: The Science of Composting. M. de Bertoldi, P. Sequi, B. Lemmes, and T. Papi, eds. Blackie, London.
12. Cartwright, D. K., and Benson, D. M. 1993. Optimization of biological control of Rhizoctonia stem rot of poinsettia by Paecilomyces lilacinus and Pseudomonas cepacia. Plant Dis. 79:301-308.
13. Cartwright, D. K., and Benson, D. M. 1994. Effect of population dynamics of Pseudomonas cepacia and Paecilomyces lilacinus on colonization of polyfoam rooting cubes by Rhizoctonia solani. Appl. Environ. Microbiol. 60:2852-2857.
14. Cartwright, D. K., and Benson, D. M. 1996. Efficacy of binucleate Rhizoctonia fungi to control Rhizoctonia stem rot of poinsettia. (Abstr.) Phytopathology 86:S37.
15. Chen, W., Hoitink, H. A. J., Schmitthenner, A. F., and Tuovinen, O. H. 1988. The role of microbial activity in suppression of damping-off caused by Pythium ultimum. Phytopathology 78:314-322.
16. Chen, Y., and Inbar, Y. 1993. Chemical and spectroscopic analyses of organic matter transformations during composting in relation to compost maturity. Pages 551-600 in: The Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects. H. A. J. Hoitink and H. M. Keener, eds. Renaissance Publications, Worthington, OH.
17. Chung, Y. R., and Hoitink, H. A. J. 1990. Interactions between thermophilic fungi and Trichoderma hamatum in suppression of Rhizoctonia damping-off in a bark-amended container medium. Phytopathology 80:73-77.
18. Chung, Y. R., Hoitink, H. A. J., Dick, W. D., and Herr, L. J. 1988. Effects of organic matter decomposition level and cellulose amendment on the inoculum potential of Rhizoctonia solani in hardwood bark media. Phytopathology 78:836-840.
19. Chung, Y. R., Hoitink, H. A. J., and Lipps, P. E. 1988. Interactions between organic matter decomposition level and soilborne disease severity. Agric. Ecosyst. Environ. 24:183-193.
20. Davey, C. B., and Papavizas, G. C. 1963. Saprophytic activity of Rhizoctonia as affected by the carbon-nitrogen balance of certain organic soil amendments. Soil Soc. Am. Proc. 27:164-167.
21. de la Cruz, J., Rey, M., Lora, J. M., Hidalgo-Gallego, A., Dominguez, F., Pintorero, J. A., Llobell, A., and Benitez, T. 1993. Carbon source control on beta-glucanases, chitinase and chitinase from Trichoderma harzianum. Arch. Microbiol. 159:316-322.
22. Elad, Y., Chet, I., and Katan, P. 1980. Trichoderma harzianum: A bio-control agent effective against Sclerotium rolfsii and Rhizoctonia solani. Phytopathology 70:119-121.
23. Garrett, S. D. 1962. Decomposition of cellulose in soil by Rhizoctonia solani Kühn. Trans. Brit. Mycol. Soc. 45:115-120.
24. Grebus, M. E., Watson, M. E., and Hoitink, H. A. J. 1994. Biological, chemical and physical properties of composted yard trimmings as indicators of maturity and plant disease suppression. Comp. Sci. Util. 2:57-71.
25. Hadar, Y., and Gorodecki, B. 1991. Suppression of germination of sclerotia of Sclerotium rolfsii in compost. Soil Biol. Biochem. 23:303-306.
26. Harman, G. E., and Björkman, T. 1998. Potential and existing uses of Trichoderma and Gliocladium for plant disease control and plant growth enhancement. Pages 229-265 in: Trichoderma and Gliocladium, Vol. 2. Enzymes, Biological Control and Commercial Applications. G. E. Harman and C. P. Kubicek, eds. Taylor & Francis, Bristol, PA.
27. Harris, A. R., and Adkins, P. G. 1998. Variability of fungal and bacterial isolates for biological control of damping-off diseases caused by Rhizoctonia solani and Pythium spp. Biol. Contr. 15:10-18.
28. Hoitink, H. A. J., and Boehm, M. J. 1999. Biocontrol within the context of soil microbial communities: A substrate-dependent phenomenon. Annu. Rev. Phytopathol. 37:427-446.
29. Hoitink, H. A. J., Inbar, Y., and Boehm, M. J. 1991. Status of compost-amended potting mixes naturally suppressive to soilborne diseases of floricultural crops. Plant Dis. 75:869-873.
30. Howell, C. R., and Staninovic, R. D. 1979. Control of Rhizoctonia solani on cotton seedlings with Pseudomonas fluorescens and with an antibiotic produced by the bacterium. Phytopathology 69:480-482.
31. Ko, W., and Hora, F. K. 1971. A selective medium for the quantitative determination of Rhizoctonia solani in soil. Phytopathology 61:203-208.
32. Kuter, G. A., Hoitink, H. A. J., and Chen, W. 1988. Effects of municipal sludge compost curing time on suppression of Pythium and Rhizoctonia diseases of ornamental plants. Plant Dis. 72:751-756.
33. Kuter, G. A., Nelson, E. B., Hoitink, H. A. J., and Madden, L. V. 1983. Fungal populations in container media amended with composted hardwood bark suppressive and conducive to Rhizoctonia damping-off. Phytopathology 73:1450-1456.
34. Kwok, O. C. H., Fahy, P. C., Hoitink, H. A. J., and Kuter, G. A. 1987. Interactions between bacteria and Trichoderma hamatum in suppression of Rhizoctonia damping-off in bark compost media. Phytopathology 77:1206-1212.
35. Lewis, J. A., Larkin, R. P., and Rogers, D. L. 1998. A formulation of Trichoderma and Gliocladium to reduce damping-off caused by Rhizoctonia solani and growth of the pathogen in soilless mix. Plant Dis. 82:501-506.
36. Lewis, J. A., and Papavizas, G. C. 1985. Effect of mycelial preparations of Trichoderma and Gliocladium on populations of Rhizoctonia solani and the incidence of damping-off. Phytopathology 75:812-817.
37. Lumsden, R. D., Lewis, J. A., and Papavizas, G. C. 1983. Effect of organic amendments on soilborne plant diseases and pathogen antagonists. Pages 51-70 in: Environmentally Sound Agriculture. W. Lockeretz, ed. Praeger Press, New York.
38. Marull, J., Pinochet, J., and Rodríguez-Kábana, R. 1997. Agricultural and municipal compost residues for control of root-knot nematodes in tomato and pepper. Comp. Sci. Util. 5:6-15.
39. Nameth, S. T. 1997. Diseases of Poinsettias. Pages 3-5 in: Ohio Florists Association Bull. No. 813.
40. Nelson, E. B., and Hoitink, H. A. J. 1982. Factors affecting suppression of Rhizoctonia solani in container media. Phytopathology 72:275-279.
41. Nelson, E. B., and Hoitink, H. A. J. 1983. The role of microorganisms in the suppression of Rhizoctonia solani in container media amended with composted hardwood bark. Phytopathology 73:274-278.
42. Nelson, E. B., Kuter, G. A., and Hoitink, H. A. J. 1983. Effects of fungal antagonists and compost age on suppression of Rhizoctonia damping-off in container media amended with composted hardwood bark. Phytopathology 73:1457-1462.
43. Phae, C. G., Saski, M., Shoda, M., and Kubota, H. 1990. Characteristics of Bacillus subtilis isolated from composts suppressing phytopathogenic microorganisms. Soil Sci. Plant Nutr. 36:575-586.
44. Puustjärvi, V., and Robertson, R. A. 1975. Physical and chemical properties. Pages 23-28 in: Peat in Horticulture. D. W. Robinson and J. G. D. Lamb, eds. Academic Press, New York.
45. Rouse, I., and Baker, R. 1978. Modeling and quantitative analysis of biological control mechanisms of Rhizoctonia solani damping-off of radish following soil amendments with cellulose and chitin. Phytopathology 68:1297-1302.
46. Stone, A. G., Traina, S. J., and Hoitink, H. A. J. 2001. Particulate organic matter composition and Pythium damping-off of cucumber. Soil Sci. Soc. Am. J. 65:761-770.
47. Tahvonen, R. 1982. The suppressiveness of Finnish light coloured sphagnum peat. J. Sci. Agric. Soc. Finland 54:345-356.
48. Tuitert, G., Szczech, M., and Bollen, G. J. 1998. Suppression of Rhizoctonia solani in potting mixes amended with compost made from organic household waste. Phytopathology 88:764-773.
49. Tunlid, A., Hoitink, H. A. J., Low, C., and White, D. C. 1989. Characterization of bacteria that suppress Rhizoctonia damping-off in bark compost media by analysis of fatty acid biomarkers. Appl. Environ. Microbiol. 55:1368-1374.
50. Weller, D. M. 1988. Biological control of soilborne plant pathogens in the rhizosphere with bacteria. Annu. Rev. Phytopathol. 26:379-407.
51. Workneh, F., van Bruggen, A. H. C., Drinkwater, L. E., and Sherman, C. 1993. Variables associated with a reduction in corky root and Phytophthora root rot of tomatoes in organic compared to conventional farms. Phytopathology 83:581-589.