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A REVIEW OF THE LITERATURE ON ERADICATION OF PLANT PATHOGENS AND NEMATODES DURING COMPOSTING, DISEASE SUPPRESSION AND DETECTION OF PLANT PATHOGENS IN COMPOST

Written By:

R. Noble and S.J. Roberts
Horticulture Research International, Wellesbourne, Warwick, CV35 9EF, UK

Published by:

The Waste and Resources Action Programme
The Old Academy, 21 Horsefair, Banbury, Oxon OX16 0AH
Tel: 01295 819900 Fax: 01295 819911 www.wrap.org.uk

Published: November 2003

ISBN: 1-84405-062-9

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Summary

Eradication of plant pathogens and nematodes during composting

Temperature-time effects and other sanitising factors of composting on 60 plant pathogen and nematode species have been reviewed. For all of the bacterial plant pathogens and nematodes, the majority of fungal plant pathogens, and a number of plant viruses, a compost temperature of 55°C for 21 days was sufficient for ensuring eradication. Shorter periods may be satisfactory but these were not always examined. The fungal plant pathogens, *Plasmodiophora brassicae*, the causal agent of clubroot of *Brassicas,* and *Fusarium oxysporum* f. sp. *lycopersici*, the causal agent of tomato wilt, were more temperature tolerant. A compost temperature of at least 65°C for up to 21 days was required for eradication. Several plant viruses, particularly Tobacco Mosaic Virus (TMV) were temperature tolerant. However, there is evidence that TMV and Tomato Mosaic Virus are degraded over time in compost, even at temperatures below 50°C.

Compost temperatures in excess of 60°C can be achieved in a range of composting systems using a wide range of feedstock wastes. However, there is insufficient information on the survival risks of pathogens in cooler zones of the compost, particularly in in-vessel systems where the compost is not turned.

Plant disease suppression associated with compost use

Numerous pot-based studies have consistently demonstrated a suppressive effect of composts on soil-borne diseases such as damping-off and root rots (*Pythium ultimum, Rhizoctonia solani, Phytophthora* spp.) and wilts (*Fusarium oxysporum* and *Verticillium dahliae*). Composts have also been shown to suppress several diseases in the field, notably *Allium* white rot. However, there is still a lack of experimental data on the disease suppressive effects of compost amendments in field experiments; so far, the effects have been generally smaller and more variable than in pot experiments. Work in the US has shown that several diseases of turf can be suppressed by top-dressing with compost. These diseases are Fusarium patch, red thread, damping-off, brown patch, dollar spot and snow mould.

Detection of plant pathogens in compost

There are a number of techniques which could potentially be used to detect the presence of plant pathogens in compost: bioassay, baiting, DNA-based (PCR polymerase chain reaction), serological (dip-stick, agglutination, ELISA enzyme linked immunosorbent assay, IF), plating on (selective) agar media, and combination methods. It is rare that methods have been developed specifically for compost. However, examples of all of these methods have been developed/proposed for the detection of fungal and bacterial pathogens in soil and could be applicable or adapted for detection in compost. Bioassays appear to have been the most frequently used methods for the detection of fungal and viral pathogens in compost, whereas dilution plating has most frequently been used for bacterial pathogens. Most recent research effort has focussed on the development of either serological or PCR-based detection methods. In general, PCR can give comparable detection limits to traditional plating assays that are the most sensitive. The claims for detection limits of direct serological assays are quite variable, but are generally poorer than plating or PCR, there is little data on the detection limits of bioassays. Critical comparisons of methods are rare and independent validation studies are almost absent. It is recommended that before implementation of any method(s) for routine quality assurance of compost, that appropriate validation studies are performed.

Introduction

Concerns about the presence of potentially harmful organisms (plant and human pathogens) are a major limitation to the increased up-take of composted waste by potential end-users in the horticultural (professional and amateur) and agricultural sectors. If compost producers were able to provide appropriate quality assurance (QA) data, it would develop increased confidence in the safety of the product and thereby increased uptake by end-users, especially professionals. The obvious way of providing QA data is to test compost for the presence of harmful micro-organisms.

There are a vast number of fungal, bacterial and viral plant pathogens; some of these are highly specific, infecting only a single crop or host species, others are more opportunistic, infecting a broad range of susceptible hosts. Clearly, end-users (commercial growers, gardeners) want to be assured that the there are no organisms present which will infect the *particular plant species* which they intend to grow.

Eradication of Plant Pathogens and Nematodes During Composting

Introduction

Eradication in the context of this literature review is defined as a reduction in the numbers of the pathogen to levels below the detection limit of the detection method used. As no detection assay can give an absolute guarantee that compost is free from a particular pathogen, this means that in some cases low levels of the pathogen in question may still be present in the compost.

The success of composting in eliminating potentially harmful pathogens is not solely a result of the heating process but also depends on the many and complex microbial interactions which may occur, as well as other compost parameters such as moisture content (Bollen 1985). The eradication of pathogens from organic wastes during composting is primarily due to:

(a) heat generated during the thermophilic phase of the composting process

(b) the production of toxic compounds such as organic acids and ammonia

(c) lytic activity of enzymes produced in the compost

(d) microbial antagonism, including the production of antibiotics, and parasitism

(e) competition for nutrients (Ryckeboer 2001)

(f) natural loss of viability of the pathogen with time

(g) compounds that stimulate the resting stages of pathogens into premature germination (Coventry *et al.* 2002).

However, heat generated during the thermophilic high temperature phase of aerobic composting appears to be the most important factor for the elimination of plant pathogens (Ryckeboer 2001). Although pathogen content may continue to decline during compost maturation, the conditions are more difficult to define for sanitisation standards, and less likely to be conducive for reliable pathogen eradication than the high temperature phase.

Methods for studying temperature-time effects on eradication

Research on the temperature-time effects on 60 plant pathogen and nematode species has been retrieved from 41 publications. The nematode and pathogen species and their associated plant diseases are listed in Tables 1 and 2. These are mainly soil-borne pathogens and pests, since these pose the greatest risk in subsequent use of composted materials. Most of this research has been conducted in composting organic wastes, although survival in other media, such as soil, water and air, is shown for comparison. For some organisms (e.g. *Pythium ultimum*) only the latter data are available.

Where eradication tests were conducted in compost, these were mostly conducted in self-heating heaps of varying size, with or without forced aeration or turning. The temperatures within such heaps vary in both

space and time. Where temperatures from such tests cannot be precisely defined, an average temperature with a ± range is quoted (Table 3). The composting tests of Coventry *et al.* (2001) were conducted in thermostatically controlled aerated flasks. Where eradication data were obtained in water or anaerobic digester liquid (Table 4), the temperatures and times needed for eradication are less than those for tests conducted in compost for the same pathogen (Table 3). This may be partly due to the effect of moisture on pathogen survival, but may also reflect the more accurate recording of temperatures and times using water baths than in heaps of compost.

The times quoted for eradication depend on the intervals used for retrieving samples for viability testing. In some cases, the first retrieval was not until three or more weeks after the start of the test (Wijnen *et al.* 1983) so that a shorter eradication time cannot be specified.

The pathogen inoculum for tests was normally infected plant material or extracted juices and suspensions. These may contain a single type or range of types of growth stages or propagules. In other work, the growth stage or propagule used for inoculum are specified (e.g. spores, sclerotia, mycelium). In all of the references, the viability of the uncomposted pathogen inoculum tested positive, with the same procedure used for testing the viability of inoculum retrieved from the compost.

The number of replicates used for testing the viability of pathogens in a particular temperature-time treatment varied greatly (Tables 3 and 4). The number of replicates was usually greater where individual propagules (spores, sclerotia, cysts) were used instead of infected plant material. In a number of references, the number of replicate samples used for testing viability was not stated.

Fungal plant pathogens

The majority of fungal pathogens tested could be eradicated by maintaining a compost temperature of 55°C for 21 days (Table 3). *Fusarium oxysporum* f.sp. *lycopersici*, the causal agent of tomato wilt, required a compost temperature of 65°C for 21 days, using infected kernels as an inoculum (Christensen *et al.* 2001). Other *Fusarium oxysporum* sub-species appeared to be less temperature tolerant when tested by other workers. Christensen *et al.* (2001) also found that *Rhizoctonia solani*, again using infected kernels as inoculum, required a compost temperature of 60°C, held for 10 days, for eradication. However, several other workers using infected plant material or mycelium as inoculum, did not find *R. solani* to be particularly temperature tolerant during composting.

Data obtained for *Plasmodiophora brassicae*, the causal agent of clubroot of Brassicas, are very variable. Lopez-Real & Foster (1985) and Bollen *at al* (1989) both found that a temperature of 54 - 55°C held for 1 - 21 days eradicated the organism. However, Ylimaki *et al.* (1983), Bruns et al (1993) and Christensen *et al.* (2001) found that temperatures of 60 - 70°C for 7 - 21 days were required for eradication. Both Bollen *et al.* (1989) and Ryckeboer *et al.* (2002b) found that *P. brassicae* could survive for long periods at lower temperatures during the maturation phase of composting. The effect of compost moisture content and feedstock composition on the temperature tolerance of *P. brassicae* is currently being studied at INRA Dijon, France as part of an EU funded project 'RECOVEG' (www.hri.ac.uk/recoveg/recoveg.htm).

Tests in water (Table 4) also showed that temperatures in excess of 65°C were required for eradication of *P. brassicae*, although the tests were only conducted for 10 minutes (Lopez-Real and Foster 1985). Tests in water also showed that *Synchytrium endobioticum*, the causal agent of potato wart disease, to be temperature tolerant (Glynne 1926). However, this pathogen is not endemic in the UK and potato wart disease is notifiable. No data were found on the eradication conditions for a number of important fungal soil-borne plant pathogens either in compost or other media. These pathogen species include the causal agents of tomato root rot (*Fusarium oxysporum* f.sp. *radicis-lycopersici*), root rot (*Phytophthora nicotianae*), Fusarium patch of turf (*Microdochium nivale*), and damping-off (*Pythium ultimum*).

Bacterial plant pathogens

All of the bacterial plant pathogens in Table 5 could be eradicated by a compost temperature of 55°C or less, held for 7 days. There is no data for eradication of *Xanthomonas campestris* pathovars e.g. *X. campestris* pv. *campestris*, the causal agent of black rot of Brassicas.

Viral plant pathogens

Cucumber Mosaic Virus, Melon Necrotic Spot Virus and Tobacco Necrosis Virus could be eradicated by a composting temperature of 55°C held for 14 days (Table 6). Tomato Spotted Wilt Virus required a temperature of 60°C for 3 days, and Cucumber Green Mottle Mosaic Virus, Pepper Mild Mottle Virus, Tobacco Mosaic Virus (TMV) and Tobacco Rattle Virus were even more temperature tolerant (Table 6). Eradication conditions for TMV were variable, but Price (1933), Bartels (1956), Hermann *et al.* (1994), Hoitink & Fahy (1986), Christensen *et al.* (2001) and Ryckeboer *et al.* (2002b) all found that temperatures in excess of 68°C for periods of longer than 20 days were needed. However, Ryckeboer *et al.* (2002b) found that TMV did not survive after a long period in compost (184 days), even at low temperature (31°C). For TMV, microbial degradation of infected plant tissue and virus particles during composting may therefore be more important in achieving eradication than temperature-time effects. The same may apply to Tomato Mosaic Virus (ToMV), which was very temperature tolerant when tested in an incubator (Avgelis and Manios 1989) (Table 6), but eradicated from a compost heap at 47°C for 10 days (Table 6).

Vectors of viruses include fungi (e.g. *Olpidium brassicae*) and nematodes. These vectors are sensitive to composting conditions (Tables 3 and 7). No data is yet available on the fungal vector of Beet Necrotic Yellow Vein Virus (BNYVV), *Polymyxa betae,* although this organism is being studied in a current EU funded project "Compost Management" QLRT 2000-01442 (www.ppo.dlo.nl/compost). Infected tomato seeds in compost may be a possible inoculum of TMV and ToMV. Hermann *et al.* (1994) reported destruction of tomato seeds in compost in 3 - 4 days at temperatures of 55 - 65°C. Christensen *et al.* 2002 also found that tomato seeds were no longer viable after exposure to a compost temperature of 60°C for 10 days, and became soft.

Plant pests

All of the nematode species in Table 7 were sensitive to temperatures of 52°C for periods of less than 1 day. Ryckeboer *et al.* 2002b showed that beet cyst nematode (*Heterodera schachtii*) had the ability to survive in compost for long periods at low temperatures (31°C). Coventry *et al.* (2001) found that onion fly larvae (*Delia antiqua*) were eradicated by a composting temperature of 50°C for 1 day.

Other compost factors involved in pathogen eradication

The moisture content of the organic waste can influence the temperature tolerance of micro-organisms, and the occurrence of dry pockets in composting material is probably the main cause of pathogen survival in heaps where eradication was expected on the basis of compost temperatures (Bollen and Volker 1996). These workers recommended a minimum compost moisture content of 40%. Bartels (1956) found no significant effect of pH on the inactivation of TMV during composting, between pH values of 3 and 8. However, the effect of compost moisture (or pH) on the thermal sensitivity of plant pathogens has not been studied in detail.

It is known that some fungal pathogens (e.g. *Phytophthora cinnamomi*) are killed after exposure to relatively high concentrations of ammonia (Gilpatrick 1969). In the first stages of composting of crop residues rich in nitrogen, ammonia probably contributes to sanitisation (Bollen and Volker 1996). Products formed under anaerobic conditions may affect pathogens. Ryckeboer *et al.* 2002a found that *Plasmodiophora brassicae* was sensitive to temperature in anaerobic digester liquid (Table 4), whereas this organism was temperature tolerant under aerobic composting conditions (Table 3).

Microbial antagonism is one of the principal factors involved in disease suppressive properties of compost (see relevant Section). The degradation of virus infected plant material and virus particles in compost has already been mentioned. However, the role of microbial antagonism in contributing to the destruction of pathogens in compost heaps has not been experimentally established (Bollen and Volker 1996).

Temperature Profiling of Commercial Composting Systems

Sanitisation standards for compost have been developed in the US by the Composting Council of the US (Leege and Thompson 1997), in the UK by WRAP and the Composting Association (Anon 2002) as well as in several other European countries (Stentiford 1996). These specify minimum compost temperatures of 55 - 65°C for periods of 3 - 14 days depending on the composting system (turned windrow, in-vessel, static aerated piles). A risk assessment of composting to dispose of catering waste containing meat recommended a minimum composting temperature of 60°C for 2 days (Gale 2002). Based on survival probabilities, this report also recommended that windrows should be turned at least three times and the composting process should last at least 14 days. Christensen *et al.* (2002) recommend even more stringent sanitary requirements i.e. 70°C for 2 days or 65°C for 4 days, with at least 5 turnings in windrow systems. However, it is not clear from the literature whether sufficiently high temperatures can be achieved using predominantly plant-based feedstocks such as green wastes that are destined to become high quality end products. Most references on temperatures during composting show mean or maximum temperatures achieved. However, of critical importance for pathogen eradication is the proportion of the compost which remains below the specified sanitisation standards. This will depend on the feedstocks used, the composting system and its management.

The following are listed by Rynk and Richard (2001) as the main categories of composting system:

- turned windrows
- passively aerated static piles
- aerated static piles
- combined turned and forced aerated windrows
- in-vessel systems
  - horizontal agitated beds
  - aerated containers
  - aerated-agitated containers
  - silo or tower reactors.

Table 8 shows the maximum temperatures recorded in the hottest and coolest zones of different composting systems with various feedstocks. Temperatures above 60°C were achieved in all the tests, except with hardwood bark waste with inorganic fertiliser. Temperatures are significantly lower in the cool zones of static or turned windrows than of in-vessel systems. However, probability studies (Gale 2002) have shown that the risk of pathogen survival in windrow systems is small, providing that the windrows achieve the stipulated average temperatures and are turned at least the specified minimum number of times. Of greater concern for pathogen survival are the cool zones in in-vessel systems where there is no or little turning. Measurements in Table 8 show that in two references, temperatures in cool zones did not exceed 50°C, even though nitrogenous feedstocks were used. With plant-based feedstocks without nitrogenous activators, these cool zones may be even cooler.

Plant Disease Suppression Associated with Compost Use

The use of composts to suppress soil-borne plant pathogens has been extensively reviewed by several authors (Hoitink and Fahy 1986;De Ceuster and Hoitink 1999a;Hoitink and Boehm 1999; Hoitink *et al.* 2001;Ryckeboer 2001). These reviews have been primarily concerned with the use of composted materials for use in container media, particularly as peat alternatives and substitutes. However, there are also a number of references on other uses of composted materials in suppressing soil-borne plant pathogens. These uses include turf grass top-dressings and field applications for vegetables.

The following mechanisms of disease control have been postulated by Hoitink and Boehm (1999):
(a) successful competition for nutrients by beneficial micro-organisms
(b) antibiotic production by beneficial micro-organisms
(c) successful parasitism against pathogens by beneficial micro-organisms
(d) activation of disease-resistance genes in plants by micro-organisms (induced systemic resistance).

Other mechanisms of control include the production of toxic or stimulatory volatile compounds from composts, changes to the physical properties of the growing medium or soil (Coventry *et al.* 2001;Smolinska 2000), and changes to soil conductivity and pH.

Disease suppressive composts have been prepared from a wide range of organic feedstocks. The most frequently used feedstocks were sewage sludge (referred to as biosolids in US literature), green waste (yard trimmings), bark and vegetable wastes.

The effects of composts on disease suppression are shown in Tables 9-12 with the following details:

- the pathogen inoculum if used, otherwise a naturally infested growing medium was used
- the crop plant (turf grass in Table 12)
- the main compost feedstocks
- the growing medium for control (untreated) plants; this was usually the same medium to which compost was added
- the rate at which compost was used, expressed either as a volumetric inclusion or application rate in tonnes per hectare
- the number of replicates used in the experiments (where stated). In some experiments, compost amendment formed part of a factorial design, but there were always at least 3 replicates with and without compost
- disease control resulting from compost amendment, expressed as percentage reduction in diseased plants or measured symptoms compared with the control medium. Where experiments were repeated, the mean value is shown.

Container media

There have been numerous glasshouse, pot-based experiments to examine the suppressive effect of composts on soil-borne pathogens. Control of the soil-borne plant pathogens *Pythium ultimum, Phytophthora* spp., *Rhizoctonia solani* and *Fusarium oxysporum* using composts has been examined by several workers (Tables 9 and 10). Suppression of these pathogens in peat or soil has been consistently demonstrated by different authors, although the level of disease control differed significantly, both within the same reference and between references. These differences can partly be explained by the compost inclusion rate, the control medium (peat or soil), the compost feedstocks used, and the degree of decomposition of the compost. There are few reports of compost amendment increasing disease severity. These are shown in Tables 9 - 11 as negative values. Krebs (1990) found that a 50% spruce bark compost increased the incidence of *Fusarium* wilt in cyclamen and black root rot in poinsettias, compared with a peat control. However, he also found less *Phytophthora* root rot in saintpaulias grown in the spruce bark mix than in the peat (Table 10). Lumsden *et al.* (1983) found that sewage sludge compost increased the incidence of pea foot rot (*Fusarium solani.* f. sp. *pisi*) (Table 9). Hoitink *et al.* (2001) also reported that composts high in nitrogen or ammonium enhance Fusarium wilts, and highly saline composts enhance *Pythium* and *Phytophthora* diseases. Erhart et al (1999) found that compost prepared from bark was suppressive to *Pythium* but compost prepared from grape marc or 'biowaste' had neutral or promoting effects to disease (Table 10). Schüler *et al* (1993) found that although foot rot of pea was suppressed by 30% compost in soil, there was no significant difference compared with 30% amendment of soil with peat.

Hoitink and Boehm (1999) state that the decomposition level of organic matter critically affects populations of antagonistic micro-organisms and hence the degree of disease control achieved. However, inconsistent levels of disease control are often achieved using apparently similar composted materials (Ryckeboer 2001). In most of the research, sterilisation of composts resulted in a loss in suppressiveness, indicating that the mechanism of disease suppression was predominantly biological. There has been a considerable amount of research into identifying the antagonistic bacteria and fungi responsible for the disease control effect of composts (Hoitink *et al.* 2001). Hoitink *et al.* (1997) state that *Bacillus* spp., *Enterobacter* spp., *Flavobacterium balustinum*, *Pseudomonas* spp., other bacterial genera and *Streptomyces* spp. as well as *Penicllium* spp., several *Trichoderma* spp., isolates of *Gliocladium virens*, and other fungi have been identified as biocontrol agents (BCAs) in compost-amended substrates.

Tilston *et al.* (2002) have examined the suppressive effects of using composts against diseases of several cereal and vegetable crop diseases, including clubroot, in pot experiments. However, direct extrapolation of this data into the field situation is difficult since compost was not diluted with soil or peat. In some references, for example Labrie et al. (2001), no peat, sand or soil controls were included in the experiments; these references have therefore been excluded from the review.

Field experiments

There has been less work on the suppression of soil-borne plant pathogens in field experiments than in pot experiments (Table 11). The suppressive effects are generally smaller and more variable than results for pot experiments. Widmer *et al* (1998) found that compost suppressed *Phytophthora nicotianae* on citrus plants in pot experiments (Table 9) but there was no effect in the field (Table 11). Abbasi *et al.* (2002), using compost prepared from cannery wastes, were able to suppress anthracnose (*Colletotrichum coccodes*) and bacterial spot (*Xanthomonas vesicatoria*) in soil grown tomato crops. Coventry *et al.* (2002) found that compost prepared from onion waste reduced the number of plants infected by *Allium* white rot (*Sclerotium cepivorum*) by over 50% in the field. Dickerson (1996, 1999) found that compost applied at 48 t ha^{-1} suppressed root rot of chile peppers whereas rates of 72 t ha^{-1} or higher encouraged the disease, possibly by increasing the salinity of the soil. However, damping-off (*Rhizoctonia solani*) was only suppressed at the higher rates of compost amendment.

Goldstein (1998) discussed the widespread use of compost prepared from different feedstocks for supressing diseases on organic and conventional crops, particularly strawberries, in the USA.

Turf grass top dressing

There has been a significant amount of research in the US on the use of composts in suppressing turf diseases such as red thread, Fusarium patch, damping-off, brown patch, dollar spot and snow mould (Table 12). Following compost applications, consistently lower levels of disease were reported than in turf treated with sand or soil, or in untreated turf. However, levels of disease control varied according to application rate, type of compost, experimental year, and between researchers. Nakasaki et al (1998) have developed a method for producing compost from grass clippings that is suppressive to large patch disease of turf (*Rhizoctonia solani*) (Table 12). However, the compost is only suppressive if inoculated with *Bacillus subtilis.*

Compost is now widely used on golf courses in the USA for suppressing turf grass disease (Block 1997).

Inoculation of composts with biocontrol agents

Composts can provide a food base for biocontrol agents (BCAs) of soil-borne pathogens (Hoitink and Boehm 1999). To improve the consistency of disease control using composts, BCAs such as *Trichoderma* spp. and *Flavobacterium balustiunum* have been added to compost amendments (De Ceuster & Hointink 1999b; Hoitink *et al.* 2001;Ryckeboer 2001, and results of Nakasaki *et al* 1998 previously discussed). Results indicate that mixtures of bacterial and fungal BCAs are more effective than single BCAs in inducing suppression of *Rhizoctonia* and *Pythium* (Ryckeboer 2001). This approach is relatively recent and is not yet widely used within Europe. Companies such as Prophyta GmbH in Germany supply BCAs for this purpose. The possibility of inoculating composts with BCAs for controlling soil-borne pathogens in vegetable crops and container plants is currently being examined in EU funded projects "RECOVEG" and "COMPOST MANAGEMENT" (www.hri.ac.uk/recoveg/recoveg.htm and www.ppo.dlo.nl/compost).

Detection of Plant Pathogens in Compost

Introduction

No detection assay can give an absolute guarantee that compost is free from a particular pathogen. Associated with any method, either explicitly or implicitly, is a limit of detection (the lowest concentration which can be detected with a reasonable statistical certainty) and/or a limit of quantitation (the lowest concentration which can be determined with acceptable precision and accuracy). The best that can be achieved with any method is to say that a particular pathogen is below the detection limit of the particular test applied. It is therefore vital to devise and use test methods which can reliably detect concentrations of the target pathogen(s) which may present a risk to end-users. There is little value in developing a method which can detect say 10^5 cells/g of compost if there is a significant risk with as few as 10^2 cells/g. Unfortunately, for most pathogens these risks have not been quantified, and so it would seem sensible to use test methods with the lowest detection limit, unless there is data to show that this is not necessary. In this respect, it is also important to consider the legal implications, should there be litigation as a result of subsequent problems. It would be difficult to convince a court that due-diligence had been exercised if a test method could have been applied with a detection limit more than 100-fold lower than the one which had been used.

Notes on literature review

There is a vast literature on the detection of plant pathogens and it would be impossible to provide a thorough review of detection in all substrates. Many detection methods can be adapted to different substrates and many detection methods have necessarily been used in studies on eradication or developed as part of larger epidemiology studies. For the purposes of this review, the examination of literature was limited to a detection of plant pathogens in compost and soil. Soil was included as it would seem reasonable that methods developed for soil could be either used directly for compost or with minimal adaptation. The one exception is a paper by Pettit *et al.*. (2002) on detection in water, which is included as an excellent example of a comparison of detection methods. A summary of the results of literature searches is given in Tables 13 and 14. Some of the methods were reported in papers on the eradication of plant pathogens during composting. However in many cases eradication was examined using material contained in nylon bags buried/suspended in the compost. Assays were then performed specifically on the material contained in the bags, therefore the assays would not always be appropriate for detection of the relevant pathogen in bulk compost.

A number of the reports/papers reviewed from the same laboratory repeated methods in previous papers; in most of these cases only a single reference is given to avoid excessive repetition.

There are a number of techniques which could potentially be used to detect the presence of plant pathogens in compost: bioassay, baiting, DNA-based (PCR), serological (dip-stick, agglutination, ELISA, IF), plating on (selective) agar media, and combination methods. All of these were represented in the literature.

Methods for detection

Bioassays

Bioassays were the most common method for the detection of soil-borne fungal pathogens in compost and are probably the oldest technique for detection and identification of plant pathogens. For pathogens which are non-culturable obligate parasites (e.g. *Plasmodiophora brassicae*, *Olpidium brassicae, Polymyxa betae*), bioassays were the only practical method before the development of serological and molecular methods.

In most of the bioassays for fungal pathogens sensitive indicator plant species are grown in samples of the test compost or soil in trays or pots. The test soil/compost is sometimes mixed/diluted with a similar quantity of sterile soil or compost containing fertilisers, etc.. Seeds of indicator species are then either sown directly into the soil/compost or young plants are transplanted. Following incubation for periods of up to several weeks, the presence of particular disease symptoms on plants is taken to indicate the presence of the pathogen. This may mean checking for damping off symptoms (*Pythium* spp., *Rhizoctonia*), wilting/vascular discoloration (*Fusarium*, *Ralstonia*), examining roots for the presence of galls (*Plasmodiophora*) or rots

(*Phytophthora, Pythium, Pyraenochaeta*). Thus the success of many bioassays depends critically on the expression of typical disease symptoms in the indicator species. This means that the environment and indicator need to be selected carefully. There is little evidence that these aspects have been well researched. In one case for *Rhizoctonia* (Christensen *et al.* 2001), there was a report that the indicator plant species although infected did not express symptoms as demonstrated by subsequent serological test on the indicator plants.

The bioassays for viruses generally follow a different principle from those for fungi or bacteria. Samples of compost are suspended in buffer which is then used to inoculate an indicator plant in a standard way. If the virus is present, the indicator plant, often a *Nicotiana* spp. produces characteristic symptoms of the virus, usually local lesions, within 7-14 d. The number of lesions is taken to provide an relative estimate of the number of virus particles in the sample extract. A major advantage of bioassay for viruses is that only *infective* virus particles are detected, whereas the direct use of a serological or molecular method may detect non-infectious virus particles.

Bioassays do not require specialist equipment and are probably the cheapest and least labour intensive of all the methods reviewed. They could be feasibly performed on-site by compost producers, using similar approaches to those indicated in the draft PAS 100 document for weeds and phytotoxicity assessment. A disadvantage with bioassays is the time taken to complete a test, which may be several weeks in the case of some fungi. However, we do not believe that this should be a major issue in the context of compost testing, as there is a considerable window of opportunity to complete this type of assay during the compost maturation phase. Alternatively one way to reduce this time is to apply a second method (e.g. ELISA) to confirm the presence of the pathogen in the test plants before symptoms have been expressed (e.g. (Christensen *et al.* 2001;Thornton *et al.* 2003), although in this case they should perhaps be more correctly considered as baiting.

Indications of detection limits or recoveries were given in only a few cases: 10^3 spores/g peat and 10^6 spores/g soil for *Plasmodiophora brassicae* (Staniaszek *et al.* 2001) and 1.7% recovery for *Polymyxa betae* (Tuitert and Bollen 1993). Nevertheless bioassays may give the most direct and easily interpretable assessment of practical risk for end-users and can effectively test for multiple pathogens. Thus, for example, the absence of any adverse symptoms on a batch of tomato seedlings grown in compost could be taken to indicate that from the practical point of view the compost is safe for the production of tomatoes. Although at first sight bioassays do not give direct quantitation of the amount of the pathogen, quantitation may be achieved via the statistical approach of 'group testing' and 'maximum likelihood estimation' (most probable numbers)(Tuitert and Bollen 1993).

Baiting

Baiting assays have some similarities with bioassays, in that susceptible plants or plant material is used to attract the pathogen or increase pathogen numbers to easily detectable levels. However, they differ from bioassays in that they do not rely on the development of disease symptoms for detection, but on the application of a secondary detection method which can be the traditional plating, serology or DNA-based. The use of baiting in combination with secondary detection by serological or DNA-based methods overcomes one of the problems with these methods: their inability to discriminate between viable and non-viable pathogen propagules.

Baiting and plating is commonly used for oomycete fungi such as *Pythium* and *Phytophthora* spp. where sterilised seeds are used as the bait for a water extract of the soil/compost and after incubation (e.g. overnight) the seeds are plated on a suitable agar medium. More recently baiting has been combined with either a serological test (Thornton *et al.* 2003;Yuen *et al.* 1998) or PCR (Lees *et al.* 2002;Nechwatal *et al.* 2001) in which the bait plant material is tested directly for the presence of the pathogen. In the case of serological methods this may overcome the problem of relatively high detection thresholds, and in the case of PCR avoids inhibitors which may be present in the compost/soil.

Plating

If the target pathogen is culturable (e.g. most bacteria and many fungi), direct plating of sample extracts or dilutions thereof on selective media is probably the most widely used method. The relatively few specific references to the use of plating methods for the detection of plant pathogens in compost is because the

approach is considered so traditional that it is not worthy of specific publication in itself and methods are generally contained in papers in other aspects of particular diseases.

Direct plating is often the most cost-effective and reliable approach, and is usually used as the reference method against which others are judged. Whilst culturing is often viewed as old technology, theoretical detection limits are usually around 10 cells/ml of extract and better than both direct PCR and serological methods. They also have the advantage that, if required, further confirmatory tests can be easily performed on suspect samples. Plating methods are generally not considered to be quick. However, the overall man-power required may be less than that for PCR or serological methods. They do require laboratory facilities but are likely to be much cheaper and easier to develop or adapt for a particular target pathogen. False-positives can be avoided completely where a suitable confirmatory test is applied.

In a comparison of methods for *Ralstonia* (Pradhanang *et al.* 2000) dilution plating on selective media has the lowest detection limit, which was only matched by PCR if combined with a pre-enrichment step.

Serological methods

There are a number of formats used in the application of serological methods. All are based on the specific interaction between an antigen on or produced by the pathogen and either a polyclonal or monoclonal antibody. The different formats provide different ways of detecting the specific antigen-antibody interaction. The two formats most commonly proposed are either ELISA (enzyme linked immunosorbent assay) or dipsticks, increasingly lateral flow devices are now being developed. There are a number of variations on ELISA, e.g. indirect or direct, competitive and double antibody sandwich (DAS), each variation may be more/less appropriate depending on the form of the antigen and the way it is presented to the assay. In the most common format (direct-DAS), the wells of a polystyrene plate are coated with a first antibody, excess is washed from the wells, then test sample is introduced and allowed to react. If present, the target antigen is captured by the first antibody and retained during a subsequent washing step before application of a second (enzyme conjugated) antibody which will attach to the immobilised target antigen. Following further washing the presence of the second antibody is detected by the addition of a substrate for the enzyme which results in a colour change. Dipsticks follow a similar principle to ELISA except that the reaction usually takes place on a nitrocellulose membrane which is attached to the end of a plastic stick which can be immersed in and then removed from the test sample, antibody reagents, and substrates. The lateral-flow (LF) format is familiar to many as they are commonly sold for home pregnancy testing. Antibodies are applied in bands across a strip of nitrocellulose membrane, the liquid sample is applied at one end and 'flows' along the strip by capillary action and any antigen present is then trapped as a band by the antibody

The accuracy of serological methods depends critically on the specificity of the particular antibody used in the reaction. In the case of fungal pathogens it is often quite difficult to produce polyclonal antibodies of the required specificity (i.e. species specific), therefore monoclonal antibodies have been produced in a number of cases.

Serologically based detection systems are very effective and reliable when used for diagnosis of infected material where the quantity of the pathogen or its metabolites are relatively high. However, the <u>reliable</u> detection limits of such systems (typically around 10^4 to 10^5 cells/ml of extract) means they may be of little diagnostic value if used for <u>direct</u> tests on materials where the average concentration of the pathogen is expected to be much lower, as would be the case with compost. Often lower numbers are quoted for the detection limits by authors. It should be borne in mind that in most cases these represent the best that has been achieved by the person who developed the test in a laboratory situation, using spiked samples and a single soil type, and have not been validated. In one of the few critical studies Otten *et al.*. (1997) showed that recovery and detection limits varied according to soil type and extraction method: with recovery values ranging from 28% from sand with $CuSO_4$ extraction to <0.1% in clay with phosphate buffered saline (PBS) extraction, and detection limits ranging from 0.02 mg/ml from sand with $CuSO_4$ to 4.0 mg/ml in clay with PBS. Another critical study of serological methods by Pettit *et al.*. (2002), although on water, indicated that dipsticks were comparable in terms of sensitivity to baiting assays and that a more sensitive zoospore trapping immunoassay gave comparable results to membrane filtration and dilution plating.

The detection limits of serological methods may be improved by combining with enrichment (Thornton *et al.* 1994;Pradhanang *et al.* 2000), or trapping (Pettitt *et al.* 2002), or plating as in immunofluorescent colony

staining (IFC) (e.g. (Elsas *et al.* 2000)). However, IFC is not suitable for routine testing due to the high cost of reagents.

In common with DNA-based methods, serological methods cannot distinguish between viable and dead cells, and therefore may not be appropriate to indicate disease risks from composts. Serological methods can be very useful as a secondary confirmation step following plating or baiting.

DNA-based methods

Over recent years, DNA polymerase chain reaction (PCR) based detection methods have been the favoured approach and focus of much research for the detection of both plant and human pathogens.

PCR is a method for *in vitro* amplification of a particular DNA sequence using specific primers. In theory, if the target DNA is present in the sub-sample presented to it (usually 20 µl), it can be detected. Thus under ideal conditions, it can detect a single pathogen cell giving a *theoretical* detection limit of around 50 cells/ml of extract.

A consistently important factor affecting the ability of PCR to detect the target DNA is the presence of inhibitors in the crude extract, thus in most cases it is necessary to first extract the DNA from the soil/compost and subject it to a purification step before PCR. Following extraction the purified sample is added to a reaction mix together with the specific primers and enzyme (DNA polymerase) and subjected to a number of cycles of denaturation, annealing and extension in a thermocycler ('PCR-machine'). Usually after around 40 cycles the reaction is stopped and the PCR products are visualised by separating them using gel electrophoresis.

In the more recently developed Real Time PCR (RT-PCR) system, a fluorescent label is incorporated which allows monitoring of reaction products *in situ* without the need for additional gel electrophoresis. This then allows some degree of quantitation of the amount of target DNA in the original sample on the basis of the time taken to get a detectable reaction product. Another advantage is that it is a 'closed system' reducing the chances of contamination which can be a problem with the original technique. However the investment in equipment is greater than for traditional PCR and design and testing of specific primers requires much more effort. Most recently, portable machines have been produced such as the SmartCycler which allow on-site detection of pathogens by RT-PCR, nevertheless such equipment still requires considerable financial investment.

Although considered to be quick (results can be obtained within 1 or 2 days of receipt of a sample), it may be expensive (licensing fees and reagents), and it requires investment in specialist laboratory equipment and facilities. It can also be costly in terms of skilled labour to develop and optimise, even if specific primers are already available for the target pathogen. In addition, reliability is often problematical when applied directly to samples, due to the presence of varying amounts of inhibitors. There can also be problems with both false-positive and false-negative results depending on the specificity of the particular primers used. Another major issue is that DNA-based methods cannot distinguish between DNA from viable and dead cells, and therefore may not provide a reliable indication of the disease risks following composting. Although there is some recognition of this aspect (Parsons *et al.* 2003), it has not been fully addressed in direct PCR methods. Of course this is not an issue when the PCR is applied following enrichment, plating or baiting.

PCR methods have now been developed for the detection of a several fungal and bacterial pathogens in soil/compost. The claims for detection limits are not always transparent, and in one of the few systematic comparisons of different methods (Pradhanang *et al.* 2000) comparable results to traditional plating on selective media were only achieved after an initial enrichment step. PCR can be very useful as a secondary confirmation step following culturing, bioassay or baiting, but obviously increases the overall cost of the assay.

Validation and routine application

Very few of the methods described in the literature have been fully characterised in terms of limits of detection, limits of quantitation, accuracy (bias and precision). Where such data has been provided, this has often been obtained by the laboratory that developed the test, usually a research laboratory. Therefore most of the claims for detection limits should be treated with considerable caution unless they have been examined independently of the method developer/proposer. Thus, there is little indication of the general

applicability and reliability of any of the methods for routine use in providing quality assurance data for compost.

We are aware of only a few methods that are used commercially. The competitive ELISA method for detection of *Pythium* spp. that cause cavity spot of carrots (White *et al.* 1996) has been used successfully to provide a predictive indication of the suitability of particular fields for carrot production, and this has been offered as a service to commercial growers by HRI. We are also aware that in Australia PCR-based detection is being offered to growers as a commercial indexing service for the soil-borne pathogens *Gaumanomyces graminis* and *Rhizoctonia solani* (Keller *et al.* 2003) and a club root indexing is being proposed (Porter *et al.* 2003). However, even though these services are offered, we are not aware of any independent validation of the protocols in use. In one of the few examples where inter-laboratory comparison has been reported (Termorshuizen *et al.* 1998) a 118-fold difference was found between laboratories with the highest and lowest mean values for *Verticillium dahliae.*

Conclusions and Gaps in Research

Fate of plant pathogens and nematodes during composting

1. The temperature-time eradication conditions of 60 plant pathogen and nematode species have been retrieved from the literature. For all of the bacterial plant pathogens and nematodes, the majority of fungal plant pathogens, and a number of plant viruses, a compost temperature of 55°C for 21 days was sufficient for ensuring eradication. In several of the references, the temperatures and times required for eradication have not been precisely determined. Shorter periods and/or lower temperatures may be satisfactory, but these were not always examined.

2. The fungal plant pathogens *Plasmodiophora brassicae*, the causal agent of clubroot disease of Brassicas, and *Fusarium oxysporum* f.sp. *lycopersici*, the causal agent of tomato wilt, were more temperature tolerant. A compost temperature of at least 65°C for up to 21 days was required for eradication. A composting period of 184 days at low temperature (31°C) was not sufficient to eradicate *P. brassicae.* However, published data for *P. brassicae* were variable, possibly due to the experimental conditions. Eradication conditions for P. brassicae are currently being examined under controlled conditions at INRA Dijon, France (www.hri.ac.uk/recoveg/recoveg.htm). There was only one reference for *F. oxysporum* f.sp. *lycopersici.*

3. Several plant viruses were temperature tolerant. These are Cucumber Green Mottle Mosaic Virus, Pepper Mild Mottle Virus, Tobacco Rattle Virus, Tomato Mosaic Virus and Tobacco Mosaic Virus (TMV). TMV requires compost temperatures in excess of 68°C for longer than 20 days for eradication.

4. TMV is degraded in compost over time, and can be eradicated after a composting period of 184 days, even at low temperature (31°C). Tomato Mosaic Virus in infected plant material can withstand over 70°C in an incubator for over 20 days but is eradicated during composting at 47°C for 10 days.

5. Temperature-time eradication conditions during composting are lacking for a number of important soil-borne plant pathogens. These include the causal agents of damping-off (*Pythium ultimum*), Fusarium patch disease of turf (*Microdochium nivale*), foot rots and wilts caused by *Fusarium oxysporum* sub-species (e.g. *radicis-lycopersici* and *lycopersici*), root rot (*Phytophthora nicotianae*), black root rot (*Thielaviopsis basicola*), and black rot of Brassicas (*Xanthomonas campestris* pv. *campestris*). However, there has been a significant amount of research on the suppression of some of these pathogens in container media or turf using composts.

6. It is not clear from the literature whether sufficiently high temperatures can be achieved using predominantly plant-based feedstocks such as green wastes, in different composting systems, to achieve sanitisation.

7. There are often compost temperature ranges of 20°C or greater within different composting systems. This is of particular importance in static or enclosed in-vessel systems where there is no turning of the feedstock wastes.

Disease suppression associated with compost use

8. Data on the effects of compost on 41 soil-borne plant pathogens has been retrieved from the literature. These include the causal agents of diseases of turf, cereals, vegetables, fruit and flower crops.

9. Following compost application to turf, consistently lower levels of diseases such as Fusarium patch, red thread, damping-off, brown patch, dollar spot and snow mould are reported than in untreated turf, or in turf treated with sand or soil.

10. There has been a significant amount of research into the use of composts to suppress soil-borne diseases in glasshouse pot-based experiments. Suppression of *Pythium ultimum*, *Phytophthora* spp., *Rhizoctonia solani* and *Fusarium oxysporum* using composts has been consistently demonstrated.

11. There has been less work on the suppression of soil-borne plant pathogens with composts in field experiments than in pot experiments. *Allium* white rot has been successfully controlled in the field using composted onion waste.

12. Levels of disease suppression were variable, even using apparently similar composted materials. The mechanisms and antagonistic micro-organisms involved in disease suppression are not fully understood. However, sterilisation of composted materials generally resulted in a loss in disease suppressiveness, indicating that the mechanism is predominantly biological.

Detection of plant pathogens in compost

13. Bioassays appear to have been the most frequently used methods for the detection of fungal and viral pathogens in compost, whereas dilution plating appears has most frequently been used for bacterial pathogens.

14. Most recent research effort has focussed on the development of either serological or PCR-based detection methods. In general it would seem that PCR detection can give comparable detection limits to traditional plating assays.

15. The claims for detection limits of direct serological assays are quite variable, but are generally poorer than plating or PCR, there is little data on the detection limits of bioassays.

16. It would be feasible for compost producers to implement the use of bioassays for on-site quality assurance, or possibly some types of serological assay, but there would be a need for such assays to be characterised in terms of detection limits and accuracy

17. If bioassays are unable to provide the required sensitivity it may be more cost-effective in the long-term for testing to be performed in specialist independent laboratories, using plating, PCR or combination assays.

18. Critical comparisons of methods are rare and independent validation studies are almost absent; therefore before the implementation of any assay (regardless of methodology) for routine quality assurance of compost it is essential that appropriate validation studies are performed to establish accuracy (i.e. bias, repeatability and reproducibility) according to the principles of ISO-5725 and that work is done to relate test results to the subsequent risk of disease.

Recommendations for Further Research Work

1. Determine the pathogens of concern to high quality compost end-users by consulting with end-users of different high quality end products.

2. The temperature-time eradication conditions of the following plant pathogens should be determined in controlled composting experiments:
Fusarium oxysporum f.sp. *lycopersici*
Fusarium oxysporum f.sp. *radicis-lycopersici*
Phytophthora nicotianae
Pythium ultimum
Microdochium nivale
Thielaviopsis basicola

Verticillium dahliae
Xanthomonas campestris pv *campestris*
UK isolates of the above pathogens should be used where available. The justification for the inclusion of these plant pathogens in further eradication tests is outlined in the next section.

3. The eradication of Tobacco Mosaic Virus in long-term (up to 200 days) composting should be determined in controlled composting experiments.

4. Develop a validated rapid plant bioassay for the detection of the causal agents of clubroot of Brassicas (*Plasmodiophora brassicae*) and tomato wilt (*Fusarium oxysporum* f.sp. *lycopersici*), since the eradication temperature-time conditions are too great to be achieved uniformly within large composting systems using plant-based wastes.

5. Although a number of important broad host range pathogens should be eradicated during successful composting, in order to provide QA for the end user, compost should be routinely tested for the presence of pathogens that may be considered to be the most frequently occurring in compost and which are most likely to cause the most problems for the most end-users. Broad host range fungal pathogens that cause a complex of damping-off and foot and root rot diseases of seedlings (i.e. *Pythium* spp., *Phytophthora* spp., *Rhizoctonia* spp.) are likely to be the most frequently occurring and most likely cause of problems in compost for both professional and amateur use. We recommend that validated assays are developed for these pathogens, in additional to those in Recommendation 4.

6. Determine time-temperature profiles of industrial-scale composting processes, and best-practice in terms of sanitisation. Temperature profiles should be obtained from different windrow and in-vessel systems using green waste and vegetable waste feedstocks. This will enable the sanitary requirements determined in this review and this research to be compared with what can be achieved on an industrial scale.

7. Disseminate the information obtained from this work to commercial compost producers and end-users.

8. The use of composts as top-dressings for the suppression of turf diseases should be evaluated under UK conditions, since this is a potentially large market for composted materials.

9. The use of composted materials (with and without biocontrol agents) to suppress plant pathogens in peat-based growing media should be examined. The efficacy of such compost amendments at inclusion rates of 20% v/v or less is of particular importance since they are less likely to affect plant growth.

10. The efficacy of composted materials in suppressing soil-borne pathogens should be examined in field-scale experiments. There is significant evidence that compost amendments to soil are effective in suppressing diseases in glasshouse pot experiments but there is insufficient field-scale data.

Justification for Inclusion of Plant Pathogens in Eradication Tests

In this literature review, there are already five compost eradication references on the causal agent of clubroot, *Plasmodiophora brassicae,* one of the fungal pathogens identified as being temperature tolerant. Further work on the precise eradication conditions for *P. brassicae* from different composting wastes with differeing moisture contents is currently being conducted at INRA Dijon, France, as part of the EU funded project 'RECOVEG'. The results of this work will be made available to WRAP at the end of 2003. There are several other fungal, bacterial and viral pathogens which need to be included in further eradication tests under composting conditions, for the following reasons:

Fusarium oxysporum f.sp. lycopersici	potential temperature tolerance only 1 previous reference in compost importance in tomato growing media
Fusarium oxysporum f.sp. radicis-lycopersici	potential temperature tolerance no previous references in compost importance in tomato growing media
Pythium ultimum	no previous references in compost importance in growing media

Microdochium nivale	no previous references in compost importance in turf grass (Fusarium patch)
Xanthomonas campestris pv campestris	no previous references in compost importance in Brassica growing media
Phytophthora nicotianae	no previous references in compost importance in tomato growing media
Verticillium dahliae	importance in growing media
Thielaviopsis basicola	importance in growing media 1 previous (unreliable) reference in compost
Tobacco Mosaic Virus	well-known high temperature tolerance may be degraded by long composting?

From data for related species (or data in soil/water) in the literature review, we would not expect *P. ultimum, V. dahliae* or *T. basicola.* to be very temperature tolerant. However, due the importance of these pathogens in growing media, they should be examined under the same controlled composting conditions as the other pathogens.

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Table 1. Fungal plant pathogens and associated diseases

Genus	Species	Sub-species	Disease	Host plants	Dissemination
Armillaria	*mellea*		honey fungus	various	soil
Aphanomyces	*euteiches*		root rot	pea	soil
Botrytis	*allii*		neck rot	onion	soil, seed
Botrytis	*cinerea*		grey mould	general	air
Colletotrichum	*coccodes*		anthracnose	*Solanaceae*	soil
Colletotrichum	*orbiculare*		anthracnose	*Cucurbitaceae*	soil
Didymella	*lycopersici*		stem rot	tomato	soil
Fusarium	*oxysporum*	*callistephi*	wilt	aster	soil
Fusarium	*oxysporum*	*dianthi*	wilt	carnation, pink	soil
Fusarium	*oxysporum*	*lilii*	scale rot	lily	soil
Fusarium	*oxysporum*	*lycopersici*	wilt	tomato	soil
Fusarium	*oxysporum*	*melongenae*	wilt	melon	soil
Fusarium	*oxysporum*	*melonis*	wilt	melon	soil
Fusarium	*oxysporum*	*narcissi*	basal rot	*Narcissus*	soil
Fusarium	***oxysporum***	***pisi***	wilt	pea	soil
Fusarium	***oxysporum***	***radicis - lycopersici***	foot and root rot	tomato	soil
Fusarium	*solani*	*cucurbitae*	wilt	*Cucurbitaceae*	soil
Gaemannomyces	***graminis***	***tritici***	take all	cereals	soil
Microdochium	***nivale***		Fusarium patch	turf	soil
Mycosphaerella	*pinodes*		foot rot	pea	soil
Olpidium	*brassicae*		vector of LBVV	various	soil
Phoma	***medicaginis***	***pinodella***	black stem	pea	soil
Phomopsis	*sclerotoides*		black rot	cucumber	soil
Phytophthora	***capsici***		root rot	pepper, various	soil
Phytophthora	*cinnamomi*		root rot, dieback	various	soil
Phytophthora	*cryptogea*		collar rot, root rot	various	soil
Phytophthora	*infestans*		potato blight	potato, tomato	air, plants
Phytophthora	***nicotianae***		root rot	various	soil
Phytophthora	*ramorum*		sudden oak death	various	soil, plants
Plasmodiophora	*brassicae*		clubroot	Brassicas	soil, plants
Pseudocercosporella	herpotrichoides		foot rot	wheat	
Pyrenocheata	*lycopersici*		corky root	tomato	soil
Pythium	*irregulare*		root rot	various	soil
Pythium	***macrosporum***		root rot	bulbous iris	soil
Pythium	***myriotylum***		damping-off, root rot	general	soil
Pythium	***ultimum***		damping-off, root rot	general	soil, debris
Pythium	***violae***		cavity spot	carrot	soil
Rhizoctonia	*solani*		damping-off	general	soil
Rhizoctonia	*solani*		black-scurf	potato	soil
Rhizoctonia	*solani*		brown or large patch	turf grass	soil
Sclerotinia	*fructigena*		brown rot	stone fruits	debris
Sclerotinia	*homoeocarpa*		dollar spot	turf grass	soil
Sclerotinia	*minor*		blight	various	soil, debris
Sclerotinia	*sclerotiorum*		watery soft rot	various	soil, air
Sclerotium	*cepivorum*		white rot	*Allium*	soil
Sclerotium	*rolfsii*		southern blight	general	soil
Septoria	*lycopersici*		leaf spot	tomato	seed
Stromatinia	*gladioli*		dry rot	gladiolus	soil
Synchytrium	*endobioticum*		wart disease	potato	soil, tubers
Taphrina	*deformans*		peach leaf curl	peach	air, water
Thielaviopsis	*basicola*		black root rot	general	soil
Verticillium	*albo-atrum*		wilt	hop	soil
Verticillium	*dahliae*		wilt	various	soil

There is no compost eradication data for highlighted pathogen species

Table 2. Plant nematodes, bacterial and viral plant pathogens and associated diseases

Genus	Species	Sub-species or pathovar	Disease or nematode	Host plants	Dissemination
Bacteria					
Agrobacterium	*tumefaciens*		crown gall	various	soil
Clavibacter	*michiganensis*	*michiganensis*	canker	tomato	soil, seed
Erwinia	*amylovora*		fire blight	apple, pear, *Rosaceae*	bees, debris
Erwinia	*carotovora*	*atroseptica*	black leg and soft rot	potato	debris, tubers, soil
Erwinia	*carotovora*	*carotovora*	soft rot	wide range	soil, debris
Erwinia	*carotovora*	*chrysanthemi*	soft rot, blight	wide range	soil, debris
Pseudomonas	*savastanoi*	*phaseolicola*		*Phaseolus* beans	seed, water, debris
Ralstonia	*solanacearum*		bacterial wilt	potato, tomato, *Solanaceae*	tubers, soil, debris
Xanthomonas	*campestris*	*campestris*	black rot	*Brassica* spp.	seed, debris, soil?
Xanthomonas	vesicatoria		bacterial spot	*Solanaceae*	seed, debris, soil?
Viruses					
Cucumber Green Mottle Mosaic Virus				cucumber	
Cucumber Mosiac Virus				various	aphids, seed
Melon Necrotic Spot Virus				*Cucurbitaceae*	sap, seed, fungi
Pepper Mild Mottle Virus				*Solanaceae*	sap
Tobacco Mosaic Virus				various	plants, debris
Tobacco Necrosis Virus				various	plants, fungi
Tobacco Rattle Virus				various	soil, fungi
Tobacco Rattle Virus			white streak disease	tulip	soil, fungi
Tomato Mosaic Virus				tomato	sap, seed
Nematodes					
Globodera	*pallida*		white potato cyst	potato, tomato	soil
Globodera	*rostochiensis*		yellow potato cyst	potato, tomato	soil
Heterodera	*schachtii*		beet cyst	beet	soil
Meloidogyne	*hapla*		northern root-knot	potato	soil
Meloidogyne	*incognita*		southern root-knot	beet	soil
Meloidogyne	*javanica*		Javanese root-knot		soil
Pratylenchus	*penetrans*		meadow	strawberry	soil

There is no compost eradication data for *Xanthomonas campestris* pathovars

Table 3. Temperature-time eradication conditions for fungal plant pathogens in compost

Genus	Species and sub-species	Temp. °C	±	Time days	Reference	Facilities & replicates
Armillaria	*mellea*	50		21	Yuen & Raabe 1984	heap (26)
Botrytis	*allii*	60	13	21	Wijnen *et al.* 1983	heap
Botrytis	*cinerea*	35		4	Lopez-Real & Foster 1985	heap (6)
Botrytis	*cinerea*	40		21	Hoitink *et al.* 1976	incubator (3)
Botrytis	*cinerea*	50		7	Hoitink *et al.* 1976	incubator (3)
Botrytis	*cinerea*	50	10	77	Hoitink *et al.* 1976	heap (4)
Colletotrichum	*coccodes*	57	12	21	Bollen *et al.* 1989	heap (12)
Didymella	*lycopersici*	35		6	Phillips 1959	heap (10)
Fusarium	*oxysporum f. sp.callistephi*	55	10	21	Bollen *et al.* 1989	heap (36)
Fusarium	*oxysporum f. sp. lilii*	57	12	21	Bollen *et al.* 1989	heap (120)
Fusarium	*oxysporum f. sp. lycopersici*	65		21	Christensen *et al.* 2001	heap (47)
Fusarium	*oxysporum f. sp. melongenae*	55	10	21	Bollen *et al.* 1989	heap (60)
Fusarium	*oxysporum f. sp. melonis*	55	10	21	Bollen *et al.* 1989	heap (80)
Fusarium	*oxysporum f. sp. melonis*	55		4	Suarez *et al.* 2003	heap (4)
Fusarium	*oxysporum f. sp. narcissi*	40		21	Bollen *et al.* 1991	heap
Fusarium	*solani f. sp. cucurbitae*	55	10	21	Bollen *et al.* 1989	heap (36)
Olpidium	*brassicae*	56	10	21	Bollen *et al.* 1989	heap (54)
Olpidium	*brassicae* (spores)	50		7	Coventry *et al.* 2002	flasks (4)
Phomopsis	*sclerotoides*	60	13	21	Wijnen *et al.* 1983	heap (70)
Phytophthora	*cinnamomi*	40		7	Hoitink *et al.* 1976	incubator (3)
Phytophthora	*cinnamomi*	50	10	77	Hoitink *et al.* 1976	heap (4)
Phytophthora	*cryptogea*	60	13	21	Bollen *et al.* 1989	heap (63)
Phytophthora	*infestans*	55	10	21	Bollen *et al.* 1989	heap (108)
Phytophthora	*ramorum*	55		14	Garbelotto 2003	incubator
Plasmodiophora	*brassicae*	55	10	21	Bollen *et al.* 1989	heap (96)
Plasmodiophora	*brassicae*	54		1	Lopez-Real & Foster 1985	heap (6)
Plasmodiophora	*brassicae*	70	10	21	Bruns *et al.* 1993	heap (8)
Plasmodiophora	*brassicae*	70		7	Ylimaki *et al.* 1983	heap (10)
Plasmodiophora	*brassicae*	60		10	Christensen *et al.* 2001	heap (46)
Pseudocercosporella	*herpotrichoides*	50		7	Dittmer et al. 1990	heap (10)
Pyrenocheata	*lycopersici*	55	10	21	Bollen *et al.* 1989	heap (60)
Pythium	*irregulare*	40		7	Hoitink *et al.* 1976	incubator (3)
Pythium	*irregulare*	50	10	77	Hoitink *et al.* 1976	heap (4)
Rhizoctonia	*solani*	57	12	21	Bollen *et al.* 1989	heap (24)
Rhizoctonia	*solani*	50		21	Yuen & Raabe 1984	heap (25)
Rhizoctonia	*solani*	40		49	Hoitink *et al.* 1976	incubator (3)
Rhizoctonia	*solani*	50		7	Hoitink *et al.* 1976	incubator (3)
Rhizoctonia	*solani*	50	10	77	Hoitink *et al.* 1976	heap (4)
Rhizoctonia	*solani*	60		10	Christensen *et al.* 2001	heap (47)
Sclerotinia	*sclerotiorum*	57	12	21	Bollen *et al.* 1989	heap (60)
Sclerotinia	*sclerotiorum* (sclerotia)	55	5	20	Dittmer *et al.* 1990	heap (2)
Sclerotium	*cepivorum*	57	12	21	Bollen *et al.* 1989	heap (36)
Sclerotium	*cepivorum* (sclerotia)	48		3	Coventry *et al.* 2002	flasks (300)
Sclerotium	*rolfsii* (sclerotia)	32		12.0	Yuen & Raabe 1984	heap (20)
Stromatinia	*gladioli*	57	12	21	Bollen *et al.* 1989	heap (140)
Thielaviopsis	*basicola*	56	7		Grushevoi & Levykh 1940	heap (3)
Verticillium	*albo-atrum*	40		7	Talboys 1961	heap (3)
Verticillium	*albo-atrum*	45		0.5	Talboys 1961	heap (3)
Verticillium	*albo-atrum*	50		0.125	Talboys 1961	heap (3)
Verticillium	*albo-atrum*	55		0.042	Talboys 1961	heap (3)
Verticillium	*albo-atrum*	60		0.01	Talboys 1961	heap (3)
Verticillium	*dahliae*	50		21	Yuen & Raabe 1984	heap (15)

Infected plant material was used as inoculum unless stated. Replicates are those used in viability tests.

Table 4. Temperature-time eradication conditions for fungal plant pathogens in soil and liquids

Genus	Species (sub-species)	Inoculum	Temp. C	Time days	Medium	Reps.	Reference
Armillaria	*mellea*	infected plants	41	0.29	water	10	Munnecke *et al.* 1976
Armillaria	*mellea*	infected plants	49	0.02	water	10	Munnecke *et al.* 1976
Botrytis	*cinerea*	spores	47	0.003	water	1000	Smith 1923
Botrytis	*cinerea*	spores	50	0.004	water	1000	Smith 1923
Botrytis	*cinerea*	filtered extract	55	0.007	water	6	Lopez-Real & Foster 1985
Fusarium	*oxysporum f.sp. dianthi*	suspension	35	3	anaer. digest		Turner *et al.* 1983
Phytophthora	*infestans*	mycelium	45		water		Spector 1956
Phytophthora	*infestans*	spores	25		water		Spector 1956
Plasmodiophora	*brassicae*	filtered extract	75	0.007	water	6	Lopez-Real & Foster 1985
Plasmodiophora	*brassicae*	infect plants	52	0.42	anaer. digest.	3	Ryckeboer *et al.* 2002a
Pythium	*ultimum*	infected plants	46	0.03	water		Baker & Cummings 1943
Pythium	*ultimum*	mycelium	45	0.08	water	3	Pullman *et al.* 1981
Pythium	*ultimum*	mycelium	50	0.008	water	3	Pullman *et al.* 1981
Rhizoctonia	*solani*	mycelium	50	0.005	water	10	Miller & Stoddard 1956
Rhizoctonia	*solani*	mycelium	39	14	water	3	Pullman *et al.* 1981
Rhizoctonia	*solani*	mycelium	50	0.007	water	3	Pullman *et al.* 1981
Sclerotinia	*fructigena*	infected plants	52		water		Spector 1956
Sclerotinia	*minor*	sclerotia	50	1.5	soil	50	Adams 1987
Sclerotinia	*minor*	sclerotia	45	3.4	soil	50	Adams 1987
Sclerotinia	*minor*	sclerotia	40	39	soil	50	Adams 1987
Sclerotium	*cepivorum*	sclerotia	50	0.25	soil	300	McLean *et al.* 2001
Sclerotium	*cepivorum*	sclerotia	45	0.5	soil	300	McLean *et al.* 2001
Sclerotium	*cepivorum*	sclerotia	40	8	soil	300	McLean *et al.* 2001
Sclerotium	*cepivorum*	sclerotia	50	9.5	soil	50	Adams 1987
Sclerotium	*cepivorum*	sclerotia	45	1.7	soil	50	Adams 1987
Sclerotium	*cepivorum*	sclerotia	40	0.8	soil	50	Adams 1987
Septoria	*lycopersici*	spores	43		water		Spector 1956
Synchytrium	*endobioticum*	sporangia	60	0.33	water	20	Glynne 1926
Taphrina	*deformans*	mycelium	46		water		Spector 1956
Thielaviopsis	*basicola*	mycelium	45	0.08	water	3	Pullman *et al.* 1981
Thielaviopsis	*basicola*	mycelium	50	0.008	water	3	Pullman *et al.* 1981
Verticillium	*albo-atrum*	mycelium	53	0.003	water	10	Miller & Stoddard 1956
Verticillium	*albo-atrum*	mycelium	47	0.003	water	10	Nelson & Wilhelm 1958
Verticillium	*albo-atrum*	microsclerotia	47	0.03	water	10	Nelson & Wilhelm 1958
Verticillium	*dahliae*	mycelium	45	0.08	water	3	Pullman *et al.* 1981
Verticillium	*dahliae*	mycelium	50	0.008	water	3	Pullman *et al.* 1981

Replicates are those used in subsequent viability tests.

Table 5. Temperature-time eradication conditions for bacterial plant pathogens in compost and other media

Bacterium	**Inoculum**	**Temp. °C**	±	**Time days**	**Medium**	**Reference**	**Facilities & replicates**
Clavibacter michiganensis michiganenesis	suspension	35		7	anaer. digest.	Turner *et al.* 1983	vessels (3)
Erwinia amylovora	infected plants	40		7	compost	Bruns *et al.* 1993	heap (7)
Erwinia amylovora	suspension	50		0.017	water	Keck *et al.* 1995	water bath (3)
Erwinia amylovora	infected plants	50		0.125	water	Keck *et al.* 1995	water bath (40)
Erwinia carotovora atroseptica	culture	50		0.01	water	Robinson & Foster 1987	water bath (3)
Erwinia carotovora carotovora	culture	50		0.02	water	Robinson & Foster 1987	water bath (3)
Erwinia chrysanthemi	infected plants	40		7	compost	Hoitink *et al.* 1976	incubator (3)
Erwinia chrysanthemi	infected plants	50	10	77	compost	Hoitink *et al.* 1976	heap (4)
Erwinia chrysanthemi	culture	50		0.03	water	Robinson & Foster 1987	water bath (3)
Pseudomonas savastanoi phaseolicola	infected plants	35		4	compost	Lopez-Real & Foster 1985	heap (6)
Pseudomonas savastanoi phaseolicola	filtered extract	55		0.007	water	Lopez-Real & Foster 1985	water bath (6)
Ralstonia solanacearum	infected plants	52		0.5	anaer. digest.	Ryckeboer *et al.* 2002a	vessels (3)

Replicates are those used in subsequent viability tests.

Table 6. Temperature-time eradication conditions for viral plant pathogens in compost and other media

Virus	Inoculum	Temp. C	±	Time days	Medium	Reps.	Reference	Facilities and notes
Cucumber Green Mottle Mosaic Virus		72		3	compost	2	Avgelis & Manios 1992	heap
Cucumber Mosiac Virus		40		0.7	water	10	Walkey & Freeman 1977	incubator
Melon Necrotic Spot Virus		55	5	14	compost	3	Suarez-Estrella *et al.* 2002	heap
Pepper Mild Mottle Virus					compost	3	Suarez-Estrella *et al.* 2002	heap, survived 3 d at 60 C and 14 d at 55 C
Tobacco Mosaic Virus	plant juice	94		0.007	water	5	Price 1933	water bath
Tobacco Mosaic Virus	plant juice	72		3	water	5	Price 1933	water bath
Tobacco Mosaic Virus	plant juice	68		20	water	5	Price 1933	water bath
Tobacco Mosaic Virus		56	7		compost		Grushevoi & Levykh 1940	heap
Tobacco Mosaic Virus		65			compost		Hermann *et al.* 1994	heap
Tobacco Mosaic Virus					compost		Hoitink & Fahy 1986	heap, survived 42 d at 70 C
Tobacco Mosaic Virus					anaer. digest.	3	Ryckeboer *et al.* 2002a	small vessels, survived 12 d at 68 C
Tobacco Mosaic Virus		31		184	compost	3	Ryckeboer *et al.* 2002b	small vessels
Tobacco Mosaic Virus		70		21	compost	16	Christensen *et al.* 2001	heap
Tobacco Mosaic Virus	plant juice	92			compost	8	Bartels 1956	water bath
Tobacco Necrosis Virus		55		3	compost	6	Lopez-Real & Foster 1985	heap
Tobacco Necrosis Virus	filtered extract	75		0.007	water	6	Lopez-Real & Foster 1985	water bath
Tobacco Necrosis Virus		50		14	compost	20	Asjes & Blom-Barnhorn 2002	incubator
Tobacco Rattle Virus					compost	7	Menke & Grossmann 1971	compost silo, survived 6 d at survived 68 C
Tobacco Rattle Virus		79		0.007	water	3	Schmelzer 1957	water bath
Tomato Mosaic Virus		47		10	compost	5	Avgelis & Manios 1989	heap
Tomato Mosaic Virus					air	5	Avgelis & Manios 1989	incubator, survived 75 d at 47 C
Tomato Mosaic Virus	seeds				air	9	Broadbent 1965	incubator, survived 22 d at 70 C
Tomato Mosaic Virus	seeds				air	9	Howles 1961	incubator, survived 22 d at 72 C
Tomato Spotted Wilt Virus		60		3	compost	4	Suarez-Estrella *et al.* 2002	heap

Infected plant material was used as inoculum unless stated.

Table 7. Temperature-time eradication conditions for plant nematodes in compost and other media

Nematode	Inoculum	Temp. °C	Time days	Medium	Reps.	Reference	Facilities and notes
Globodera pallida	cysts	35	10	anaer. digest.	100	Turner *et al.* 1983	vessels
Globodera rostochiensis	cysts	33		compost		Sprau 1967	test in heap
Heterodera schachtii	cysts	52	0.02	anaer. digest.	200	Ryckeboer *et al.* 2002a	vessels
Heterodera schachtii	cysts			compost	200	Ryckeboer *et al.* 2002b	small vessels, survived 185 d at 31 C
Meloidogyne hapla	infected plants	49	0.005	water	5	Goheen and McGrew 1954	water bath test
Meloidogyne hapla	infected tubers	49	0.05	water	12	Martin 1968	water bath test
Meloidogyne incognita	infected plants	57	0.79	compost	4	Menke & Grossmann 1971	test in composting silo
Meloidogyne incognita	infected plants	52	0.5	anaer. digest.	3	Ryckeboer *et al.* 2002a	vessels
Meloidogyne javanica	infected tubers	46	0.05	water	10	Martin 1968	water bath test
Pratylenchus penetrans	infected plants	49	0.005	water	5	Goheen & McGrew 1954	water bath test

Replicates are those used in subsequent viability tests.

Table 8. Maximum temperatures recorded in the hottest and coolest zones of different composting systems with various feedstocks

Composting system	Feedstocks wastes	Maximum temperature, °C hot zone	Maximum temperature, °C cool zone	Composing time, days	Reference
Static pile	grass cuttings, hop, cattle	73	30	7	Lopez-Real & Foster 1985
Static pile	green waste, straw	59	45	23	Dittmer *et al.* 1990
Turned bin	green waste	69	22	24	Yuen & Raabe 1984
Turned stack	hardwood bark, ammon. nitrate	50	45	80	Hoitink *et al.* 1976
Turned windrow	straw, poultry, horse manure	79	43	8	Miller *et al.* 1989
Turned windrow	municipal organic, wood chips	70	27	104	Bruns *et al.* 1993
Aerated heap	sewage sludge, wood chips	75	50	21	MacGregor *et al.* 1981
Aerated heap	green waste, horse manure	66	52	67	Bollen *et al.* 1989
Silo	municipal organic	68	52	1	Menke & Grossmann 1971
In-vessel (Sirocco)	municipal organic, green	75	70	12	Wallace 2002
In-vessel (Sirocco)	vegetable, green	63	56	12	Wallace 2002
In-vessel reactor	municipal organic	68	59	31	de Bertoldi *et al.* 1988
In-vessel tunnel	sewage sludge	70	50	28	Christensen *et al.* 2002
In-vessel tunnel	straw, poultry manure	72	62	11	Miller *et al.* 1990
In-vessel tunnel	straw, poultry, horse manure	60	55	7	Macauley & Perrin 1994
In-vessel tunnel	straw, poultry manure	72	50	4	Gerrits & van Griensven 1990

Table 9. Use of composted materials to suppress plant diseases in container experiments with soil or sand

Pathogen Genus	Species	Inoculum	Disease	Crop plant(s)	Compost feedstocks	Rate v/v %	Control %	Reference
Aphanomyces	*euteiches*	zoospores	root rot	pea	sewage sludge	10	86	Lumsden *et al.* 1983
Fusarium	*culmorum*	mycelium	foot rot	winter wheat	green waste	100	55	Tilston *et al.* 2002
Fusarium	*oxysporum f. sp. basilici*	conidia	wilt	basil	sewage sludge, poplar bark	25	19	Ferrara *et al.* 1996
Fusarium	*oxysporum f. sp. melonis*	mycelium	wilt	melon	sewage sludge	10	60	Lumsden *et al.* 1983
Fusarium	*solani f. sp. pisi*	natural	foot rot	pea	sewage sludge	10	-200	Lumsden *et al.* 1983
Gaeumannomyces	*graminis f. sp. tritici*	mycelium	take all	winter wheat	green waste	100	52	Tilston *et al.* 2002
Mycosphaerella	*pinodes*	spores	foot rot	pea	kitchen, green wastes	30	16	Schüler *et al.* 1993
Phoma	*medicaginis f. sp. pinodella*	pycniospores	black stem	garden pea	green waste	100	49	Tilston *et al.* 2002
Phytophthora	*capsici*	mycelium	crown rot	pepper	sewage sludge	10	43	Lumsden *et al.* 1983
Phytophthora	*nicotianae*	chlamydospores	root rot	citrus	municipal waste	20	29	Widmer *et al.* 1998
Phytophthora	*nicotianae*	mycelium	root rot	waratah	Eucalyptus bark	100	66	Hardy & Sivasith. 1991
Plasmodiophora	*brassicae*	spores	clubroot	chinese cabbage	green waste	100	99	Tilston *et al.* 2002
Pseudocercosporella	*herpotrichoides*	mycelium	eyespot	winter wheat	green waste	100	97	Tilston *et al.* 2002
Pythium	*aphanidermatum*	natural	damping-off	bean	sewage sludge	10	0	Lumsden *et al.* 1983
Pythium	*aphanidermatum*	mycelium	damping-off	cucumber	municipal waste	20	56	Ben-Yephet & Nelson, 1999
Pythium	*macrosporum*	mycelium	root	bulbous iris	veg., fruit, green waste	1	+	van Os *et al,* 1997
Pythium	*myriotylum*	natural	blight	bean	sewage sludge	10	63	Lumsden *et al.* 1983
Pythium	*myriotylum*	mycelium	damping-off	cucumber	municipal waste	20	23	Ben-Yephet & Nelson, 1999
Pythium	*myriotylum*	mycelium	damping-off	cucumber	leaf waste	20	46	Ben-Yephet & Nelson, 1999
Pythium	*ultimum*	mycelium	damping-off	beetroot, pea	municipal waste	8, 10	63, 43	Schüler *et al.* 1989
Pythium	*ultimum*	mycelium	damping-off	cucumber	yard waste	20	0	Ryckeboer 2001
Pythium	*ultimum*	mycelium	damping-off	cucumber	veg., fruit, green waste	20	49	Ryckeboer 2001
Pythium	*ultimum*	mycelium	damping-off	Impatatiens	sewage sludge, poplar bark	25	46	Ferrara *et al.* 1996
Pythium	*ultimum*	mycelium	damping-off	cucumber, beet	sewage sludge, poplar bark	25	69, 20	Ferrara *et al.* 1996
Pythium	*ultimum*	natural	root rot	pea, bean	sewage sludge	10	0	Lumsden *et al.* 1983
Ralstonia	*solananacearum*	suspension	wilting	tomato	municipal waste	5	45	Schönfeld *et al.* 2003
Rhizoctonia	*solani*	mycelium	damping-off	pea	municipal waste	10	33	Schüler *et al.* 1989
Rhizoctonia	*solani*	mycelium	damping-off	radish	green waste	20	0	Ryckeboer 2001
Rhizoctonia	*solani*	mycelium	damping-off	radish	veg., fruit, green waste	20	41	Ryckeboer 2001
Rhizoctonia	*solani*	mycelium	damping-off	basil, bean	sewage sludge, poplar bark	20	0	Ferrara *et al.* 1996
Rhizoctonia	*solani*	mycelium	damping-off	bean, radish	sewage sludge	10	57, 64	Lumsden *et al.* 1983
Sclerotinia	*minor*	sclerotia	lettuce drop	lettuce	sewage sludge	10	53	Lumsden *et al.* 1983
Sclerotium	*cepivorum*	sclerotia	white rot	onion	vegetable waste	50	55	Coventry *et al.* 2002
Thielaviopsis	*basicola*	natural	black root	bean	sewage sludge	10	0	Lumsden *et al.* 1983

At least 5 replicates with and without compost were used in each experiment. Control is expressed as percentage reduction in disease symptoms compared with soil or sand.

Table 10. Use of composted materials to suppress plant diseases in container experiments with peat

Genus	Species	Inoculum	Disease	Crop plant	Main compost feedstocks	Rate v/v %	Control %	Reference
Colletrichum	*orbiculare*	conidia	anthracnose	cucumber	spruce bark	100	36	Zhang *et al.*,1996
Fusarium	*oxysporum f. sp. basilici*	conidia	wilt	sweet basil	cattle, poultry manures, straw	100	42	Reuveni *et al.* 2002
Fusarium	*oxysporum f. sp. chrysanthemi*	conidia	wilt	chrysanth.	hardwood bark	50	64	Chef *et al.* 1983
Fusarium	*oxysporum f. sp. cyclaminis*	natural	wilt	cyclamen	spruce bark	50	-139	Krebs 1990
Fusarium	*oxysporum f. sp. lycopersici*	conidia	wilt	tomato	sewage sludge, green waste	10	54	Cotxarrera *et al.* 2002
Fusarium	*oxysporum f. sp. lycopersici*	conidia	wilt	tomato	cork	100	53	Trillas *et al.* 2002
Fusarium	*oxysporum f. sp. lycopersici*	conidia	wilt	tomato	grape marc	100	93	Trillas *et al.* 2002
Fusarium	*oxysporum f. sp. lycopersici*	mycelium	wilt	tomato	paper mill sludge	25	57	Pharand *et al.* 2002
Fusarium	*oxysporum f. sp. radicis-lycopersici*	mycelium	foot root rot	tomato	paper mill sludge	25	43	Pharand 2002
Phytophthora	*cactorum*	zoospores	collar rot	apple	hardwood bark	50	60	Spring *et al.* 1980
Phytophthora	*cinnamomi*	mycelium	root rot	lupin	vegetable, fruit, green waste	20	53	Tuitert & Bollen 1996
Phytophthora	*cinnamomi*	mycelium	root rot	lupin	hardwood bark	60	38	Hoitink *et al.* 1977
Phytophthora	*fragariae f.sp. fragariae*	zoospores	red core	strawberry	green waste	100	66	Pitt *et al.* 1998
Phytophthora	*nicotianae*	mycelium	root rot	saintpaulia	spruce bark	50	27	Krebs 1990
Pythium	*aphanidermatum*	oospores	damping-off	cucmber	liquorice roots	50	53	Hadar & Mandelbaum 1986
Pythium	*aphanidermatum*	oospores	damping-off	cucmber	cattle manure	66	85	Mandelbaum & Hadar 1997
Pythium	*aphanidermatum*	mycelium	root rot	cucumber	spruce bark	100	20	Zhang *et al.* 1996
Pythium	*ultimum*	mycelium	root rot	cucumber	spruce bark	100	20	Zhang *et al.* 1996
Pythium	*ultimum*	mycelium	damping-off	cucumber	vegetable, fruit, green waste	20	71	Ryckeboer 2001
Pythium	*ultimum*	mycelium	damping-off	cucumber	hardwood bark	50	63	Chen *et al.* 1987
Pythium	*ultimum*	mycelium	crown rot	poinsettia	hardwood bark	50	23	Daft *et al.* 1979
Pythium	*ultimum*	mycelium	damping-off	pea	bark	30	75	Erhart *et al.* 1999
Pythium	*ultimum*	mycelium	damping-off	pea	grape marc	30	-30	Erhart *et al.* 1999
Rhizoctonia	*solani*	mycelium	damping-off	cucumber	vegetable, fruit, green waste	20	60	Tuitert *et al.* 1998
Rhizoctonia	*solani*	mycelium	damping-off	cucumber	vegetable, fruit, green waste	20	75	Tuiert & Bollen 1996
Rhizoctonia	*solani*	mycelium	damping-off	radish	green waste	20	65	Ryckeboer 2001
Rhizoctonia	*solani*	mycelium	damping-off	radish	vegetable, fruit, green waste	20	0	Ryckeboer 2001
Rhizoctonia	*solani*	mycelium	damping-off	sugar beet	vegetable, fruit, green waste	20	75	Ryckeboer 2001
Rhizoctonia	*solani*	mycelium	damping-off	radish	hardwood bark	36	81	Nelson & Hoitink 1983
Rhizoctonia	*solani*	mycelium	damping-off	poinsettia	hardwood bark	50	44	Daft *et al.* 1979
Rhizoctonia	*solani*	mycelium	damping-off	poinsettia	municipal waste	20	40	Kuter *et al.* 1988
Thielaviopsis	*basicola*	natural	black root rot	poinsettia	spruce bark	50	-59	Krebs 1990
Verticillium	*dahliae*	conidia	wilt	tomato	cork	100	70	Borrero *et al.* 2002

At least 4 replicates with and without compost were used in each experiment. Control is expressed as percentage reduction in disease symptoms compared with peat.

Table 11. Use of composted materials to suppress diseases in field experiments

Pathogen Genus	Species	Inoculum	Disease	Crop plant	Main compost feedstocks	Rate %w/w	Rate t / ha	Control %	Reference
Colletotrichum	*coccodes*	natural	anthracnose	tomato	cannery wastes		13.5	35	Abbasi *et al.* 2002
Fusarium	*oxysporum f.sp. dianthi*	natural	wilt	carnation	poplar bark	30		0	Pera & Filippi 1987
Phytophthora	*capsici*	natural	root rot	chile pepper	sewage sludge		48	35	Dickerson 1996
Phytophthora	*capsici*	natural	root rot	chile pepper	sewage sludge		72	-91	Dickerson 1996
Phytophthora	*capsici*	natural	root rot	pepper	sewage sludge, green waste		220	0	Kim *et al.* 1997
Phytophthora	*nicotianae*	chlamydospores	root rot	citrus	municipal waste		20	0	Widmer *et al.* 1999
Pythium	*ultimum*	natural	damping-off	lettuce	chicken manure		10	26	Gamliel & Stapleton 1993
Rhizoctonia	*solani*	mycelium	damping-off	pea	sewage sludge		17	29	Lewis *et al.* 1992
Sclerotium	*cepivorum*	sclerotia	white rot	onion	onion waste		335	56	Coventry *et al.* 2002
Verticillium	*dahliae*	microsclerotia	early dieing	potato	spent mushroom compost		15	9	La Mondia *et al,* 1999
Xanthomonas	*vesicatoria*	suspension	bacterial spot	tomtao	cannery wastes		62	21	Abbasi *et al.* 2002

At least 4 replicates with and without compost were used in each experiment

Table 12. Use of composted materials to suppress diseases of turf grass

Pathogen Genus	Species	Inoculum	Disease	Main compost feedstocks	Control medium	Rate %v/v	Rate t DM/ha	Control %	Reference
Laetisaria	*fuciformis*	natural	red thread	sewage sludge	sand	20		51	Nelson & Boehm 2002
Laetisaria	*fuciformis*	natural	red thread	green waste	sand	20		0	Nelson & Boehm 2002
Microdochium	*nivale*	mycelium	Fusarium patch	bark, poultry manure	soil		4.9	64	Boulter *et al* 2002b
Microdochium	*nivale*	mycelium	Fusarium patch	bark, poultry manure	soil		9.7	84	Boulter *et al* 2002b
Pythium	*graminicola*	natural	damping-off	sewage sludge	sand	20		63	Nelson & Boehm 2002
Pythium	*graminicola*	mycelium	damping-off	brewery and sewage sludges	sand	30	0.5	72	Craft & Nelson 1996
Rhizoctonia	*solani*	natural	brown patch	sewage sludge	sand	20		42	Nelson & Boehm 2002
Rhizoctonia	*solani*	natural	brown patch	green waste	sand	20		39	Nelson & Boehm 2002
Rhizoctonia	*solani*	mycelium	large patch	grass clippings	soil	10		47	Nakasaki *et al* 1998
Sclerotina	*homoeocarpa*	natural	dollar spot	sewage sludge	nil	30	5	27	Nelson & Craft 1992
Sclerotina	*homoeocarpa*	mycelium	dollar spot	bark, poultry manure	nil		7.2	50	Boulter *et al* 2002a
Sclerotina	*homoeocarpa*	mycelium	dollar spot	bark, poultry manure	nil		14.7	66	Boulter *et al* 2002a
Sclerotina	*homoeocarpa*	natural	dollar spot	sewage sludge	sand	20		40	Nelson & Boehm 2002
Sclerotina	*homoeocarpa*	natural	dollar spot	green waste	sand	20		5	Nelson & Boehm 2002
Typhula	*incarnata*	natural	blight, snow mold	sewage sludge	sand	20		70	Nelson & Boehm 2002
Typhula	*ishikariensis*	mycelium	blight, snow mold	bark, poultry manure	soil		4.9	39	Boulter *et al* 2002b
Typhula	*ishikariensis*	mycelium	blight, snow mold	bark, poultry manure	soil		9.7	82	Boulter *et al* 2002b

At least 4 replicates with and without compost were used in each experiment

Table 13. Summary of detection methods for fungal plant pathogens in compost and/or soil.

Pathogen	Species	subsp/pv	Detection in:	Method	Medium	Reference	Detection Limit	Notes
Fungi								
Botrytis	*allii*		compost	bioassay	onion bulbs	Bollen *et al.* 1989		
Botrytis	*cinerea*		compost	plating	PDA, selective agar	Hoitink *et al.* 1976		
Coletotrichum	*coccoides*		soil	PCR		Cullen *et al.* 2000		
Colletototrichum	*coccodes*		compost	bioassay	Egg plant	Bollen *et al.* 1989		
Didymella	*lycopersici*		compost	bioassay	Tomato	Phillips 1959		
Fusarium	*oxysporum*		compost	bioassay	Tomato	Christensen *et al.* 2001		
Fusarium	*oxysporum*		compost	bioassay	various	Bollen *et al.* 1989		
Fusarium	*oxysporum*		digestor liquor	enrichment and plating	Czapek Dox and PSA	Turner *et al.* 1983	3.69 spores/ml	
Fusarium	*oxysporum*	*ciceris*	soil	PCR		Garcia-Pedrajas *et al.* 1999		
Gaeumannomyces	*graminis*		soil	PCR		Keller *et al.* 1995		
Helminthosporium	*solani*		soil	PCR		Cullen *et al.* 2000		
Macrophomina	*phaseolina*		soil	flotation + plating		Chun & Lockwood 1985		microsclerotia 95% recovery
Olpidium	*brassicae*		compost	bioassay	lettuce	Bollen *et al.* 1989		
Phomopsis	*sclerotioides*		compost	bioassay	gherkin	Bollen *et al.* 1989		
Phytophthora	*cactorum*		soil	bioassay	safflower	Banihashemi & Mitchell 1975		
Phytophthora	*cinnamomi*		compost	baiting + plating	lupin	Hoitink *et al.* 1976		
Phytophthora	*cinnamomi*		soil	bioassay	lupin	Aryantha *et al.* 2000		
Phytophthora	*cinnamomi*		water ?	chemotaxis + dipstick		Cahill & Hardham 1994b	40 spores/ml	
Phytophthora	*cinnamomi*		soil	dipstick		Cahill & Hardham 1994a	2.5E2 spores/ml of extract	
Phytophthora	*cinnamomi*		compost	plating	selective agar	Hoitink *et al.* 1976		
Phytophthora	*clandestina*		soil	bioassay	clover	Purwantara *et al.* 1996		
Phytophthora	*infestans*		compost	bioassay	potato tuber disks	Bollen *et al.* 1989		
Phytophthora	*nicotaniae*		soil	dipstick		Gautam *et al.* 1999	10 spores/ml of extract	
Phytophthora	*quercina/citricola*		soil	baiting + PCR	oak leaflets	Nechwatal *et al.* 2001		
Phytophthora	spp.		water	baiting + plating	hemp/rhodedendron	Pettitt *et al.* 2002		
Phytophthora	spp.		water	dipstick	nitrocellulose	Pettitt *et al.* 2002		20% recovery
Phytophthora	spp.		soil	ELISA		Timmer *et al.* 1993		
Phytophthora	spp.		water	filtration + plating	PDA	Pettitt *et al.* 2002		76% recovery
Phytophthora	spp.		soil	plating	selective media	Timmer *et al.* 1993		

Table 13. Summary of detection methods for fungal plant pathogens in compost and/or soil.

Pathogen	Species	subsp/pv	Detection in:	Method	Medium	Reference	Detection Limit	Notes
Phytophthora	spp.		water	zoospore trapping immunoassay	nitrocellulose	Pettitt *et al.* 2002		87% recovery
Plasmodiophora	*brassicae*		compost	bioassay	chinese cabbage	Bollen 1985		
Plasmodiophora	*brassicae*		compost	bioassay	*Brassica juncea*	Ryckeboer 2001		based on (Buckzacki *et al.* 1975)
Plasmodiophora	*brassicae*		compost	bioassay	*Brassica juncea*	Christensen *et al.* 2001		
Plasmodiophora	*brassicae*		compost	bioassay	chinese cabbage	Bollen *et al.* 1989		
Plasmodiophora	*brassicae*		peat	bioassay	chinese cabbage	Staniaszek *et al.* 2001	1E3 spores/g	
Plasmodiophora	*brassicae*		soil	bioassay	chinese cabbage	Wallenhammar 1996		
Plasmodiophora	*brassicae*		soil	bioassay	chinese cabbage	Staniaszek *et al.* 2001	1E6 spores/g	
Plasmodiophora	*brassicae*		soil	ELISA		Wakeham & White 1996	1E2 spores/g	
Plasmodiophora	*brassicae*		soil	PCR		Wallenhammar & Arwidsson 2001		
Plasmodiophora	*brassicae*		soil/peat	PCR		Staniaszek *et al.* 2001	1E3 spores/g	
Polymyxa	*betae*		soil	bioassay	Beet	Tuitert & Bollen 1993		1.7% recovery
Pyraenochaeta	*lycopersici*		compost	bioassay	Tomato	Bollen *et al.* 1989		
Pythium	*aphanidermatum*		soil	baiting	oat seeds	Priou & French 1997	1 oospore/g soil	
Pythium	*aphanidermatum*		soil	baiting + plating	Cucumber	Watanabe 1984		
Pythium	*aphanidermatum*		soil	bioassay	Cucumber	Stanghellini & Kronland 1985		
Pythium	*aphanidermatum*		soil	plating	selective media	Stanghellini et al. 1982		
Pythium	spp.		water	baiting + plating	hemp/rhodendron	Pettitt *et al.* 2002		
Pythium	spp.		compost	baiting + plating	Lupin	Hoitink *et al.* 1976		
Pythium	spp.		compost	bioassay	Cucumber	Mandelbaum & Hadar 1997		
Pythium	spp.		water	dipstick	nitrocellulose	Pettitt *et al.* 2002		20% recovery
Pythium	spp.		water	filtration + plating	PDA	Pettitt *et al.* 2002		76% recovery
Pythium	spp.		soil	plating	selective medium	Conway 1985		
Pythium	spp.		water	zoospore trapping immunoassay	nitrocellulose	Pettitt *et al.* 2002		87% recovery
Pythium	*ultimum*		soil	baiting + ELISA	bean/cabbage/beet	Yuen *et al.* 1998		
Pythium	*violae/sulcatum*		soil/compost	competive ELISA		Lyons & White 1992		
Rhizoctonia	*solani*		soil	baiting + LF		Thornton *et al.* 2003		
Rhizoctonia	*solani*		soil	baiting + PCR/RT-PCR		Lees *et al.* 2002		
Rhizoctonia	*solani*		compost	baiting + plating	water agar	Kooistra 1983		

Table 13. Summary of detection methods for fungal plant pathogens in compost and/or soil.

Pathogen	Species	subsp/pv	Detection in:	Method	Medium	Reference	Detection Limit	Notes
Rhizoctonia	*solani*		compost	bioassay	Cucumber	Tuitert & Bollen 1996		
Rhizoctonia	*solani*		compost	bioassay	beet	Hoitink *et al.* 1976		
Rhizoctonia	*solani*		compost	bioassay	potato	Bollen *et al.* 1989		
Rhizoctonia	*solani*		compost	bioassay + ELISA	*Phaseolus vulgaris*	Christensen *et al.* 2001		only detected in ELISA on bait plants
Rhizoctonia	*solani*		soil	ELISA		Otten *et al.* 1997	0.02 to 4 mg/ml	varied with soil and extraction
Rhizoctonia	*solani*		soil	ELISA		Thornton & Gilligan 1999		
Rhizoctonia	*solani*		soil	enrichment and ELISA	selective medium	Thornton *et al.* 1994		
Rhizoctonia	*solani*		soil	immunomagnetic beads		Thornton 1996		
Rhizoctonia	*solani*		soil	PCR/RT-PCR		Lees *et al.* 2002	0.5 mg sclerotia/g soil	
Rhizoctonia	*solani*		soil	plating		Doornik 1981		
Rhizoctonia	*solani*		soil	plating		Gangopadhyay & Grover 1985		
Sclerotinia	*cepivorum*		soil/compost	bioassay	onion seedlings	Clarkson *et al.* 2002		
Sclerotinia	*cepivorum*		compost	bioassay	onion bulbs	Bollen *et al.* 1989		
Sclerotinia	*sclerotiorum*		compost	bioassay	Cucumber	Bollen *et al.* 1989		
Spongospora	*subterranea*		soil	ELISA		Walsh *et al.* 1996	100 spore balls/g soil	
Spongospora	*subterranea*		soil	PCR		Bell *et al.* 1999	5 spore balls/g soil	
Spongospora	*subterranea*		soil	PCR		Cullen *et al.* 2000		
Spongospora	*subterranea*		soil	wet seiving		Pratt 1976		
Stromatinia	*gladioli*		compost	bioassay	Gladiolus	Bollen *et al.* 1989		
Verticillium	*dahliae*		soil	bioassay	Egg plant	Nagtzaam *et al.* 1997		
Verticillium	*dahliae*		soil	dry seiveing and plating		Termorshuizen *et al.* 1998		
Verticillium	*dahliae*		soil	wet seiving and plating		Harris *et al.* 1993		
Verticillium	spp.		soil	PCR		Platt & Mahuku 2000		
Verticillium	spp.		soil	plating		Platt & Mahuku 2000		

Table 14. Summary of detection methods for bacterial and viral plant pathogens in compost and/or soil.

Pathogen	Species	subsp/pv	Detection in:	Method	Medium	Reference	Detection Limit	Notes
Bacteria								
Agrobacterium	*tumefaciens*		soil	bioassay	Kalenchoe	Romeiro *et al.* 1999		
Clavibacter	*michiganense*		digestor liquor	enrichment and plating	D2 broth and SNA	Turner *et al.* 1983	369 cfu/ml	
Erwinia	*amylovora*		compost	dilution plating + ELISA	CCT	Ryckeboer 2001		
Erwinia	*chrysanthemi*		compost	dilution plating and path test	selective agar	Hoitink *et al.* 1976		
Ralstonia	*solanacearum*		soil	bioassay	Tomato	Pradhanang *et al.* 2000	7.5E5 cfu/g	
Ralstonia	*solanacearum*		soil	bioassay	Tomato	van der Wolf *et al.* 2000	1E4 cfu/g	
Ralstonia	*solanacearum*		soil	dilution plating	SMSA	Pradhanang *et al.* 2000	1E2 cfu/g	
Ralstonia	*solanacearum*		compost	dilution plating + ELISA	SMSA	Ryckeboer 2001		
Ralstonia	*solanacearum*		soil	dilution plating + PCR	PCCG	Ito *et al.* 1998		
Ralstonia	*solanacearum*		soil	ELISA		Pradhanang *et al.* 2000	7.5E5 cfu/g	
Ralstonia	*solanacearum*		soil	enrichment + ELISA	SMSA	Pradhanang *et al.* 2000	1E4 cfu/g	
Ralstonia	*solanacearum*		soil	enrichment + PCR	SMSA	Pradhanang *et al.* 2000	1E2 cfu/g	
Ralstonia	*solanacearum*		soil	IFC + PCR		Elsas *et al.* 2000	1E2 cfu/g	
Ralstonia	*solanacearum*		soil	PCR		Poussier *et al.* 2002		
Ralstonia	*solanacearum*		soil	PCR		Lee & Wang 2000		
Streptomyces	*scabies*		soil	PCR		Cullen *et al.* 2000		
Xanthomonas	*campestris*	*campestris*	soil	dilution plating	FS	Fukui *et al.* 1994		
Xanthomonas	*campestris*	*campestris*	compost	dilution plating	FS + mCS20ABN	Roberts, unpublished	7.5 cfu/g	
Viruses								
CGMV			compost	bioassay	Cucumber	Avgelis & Manios 1992		
TMV			compost	bioassay	Tobacco	Ryckeboer 2001		
TMV			compost	bioassay + ELISA	Tobacco	Christensen *et al.* 2001		
ToMV			compost	bioassay	Tobacco	Avgelis & Manios 1989		