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REVIEW ARTICLE

Eradication of plant pathogens and nematodes during composting: a review

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The effects of temperature–time combinations and other sanitizing factors during composting on 64 plant pathogenic fungi, plasmodiophoromycetes, oomycetes, bacteria, viruses and nematodes were reviewed. In most cases pathogen survival was determined by bioassays of unknown sensitivity and minimum detection limits of 5% infection or more. For 33 out of 38 fungal and oomycete pathogens, all seven bacterial pathogens and nine nematodes, and three out of nine plant viruses, a peak temperature of 64–70°C and duration of 21 days, were sufficient to reduce numbers to below the detection limits of the tests used. Shorter periods and/or lower temperatures than those quoted in these tests may be satisfactory for eradication, but they were not always examined in detail in composting systems. *Plasmodiophora brassicae* (clubroot of *Brassica* spp.), *Fusarium oxysporum* f.sp. *lycopersici* (tomato wilt) and *Macrophomina phaseolina* (dry root rot) were more temperature-tolerant, as they survived a peak compost temperature of at least 62°C (maximum 74°C) and a composting duration of 21 days. *Synchytrium endobioticum* (potato wart disease) survived in water at 60°C for 2 h, but was not examined in compost. For *Tobacco mosaic virus* (TMV), peak compost temperatures in excess of 68°C and composting for longer than 20 days were needed to reduce numbers below detection limits. However, TMV and *Tomato mosaic virus* (TomMV) were inactivated over time in compost, even at temperatures below 50°C. Temperatures in excess of 60°C were achieved in different composting systems, with a wide range of organic feedstocks. The potential survival of plant pathogens in cooler zones of compost, particularly in systems where the compost is not turned, has not been quantified. This may be an important risk factor in composting plant wastes.

Keywords: compost, sanitization, survival, temperature

Introduction

Concerns about the presence of plant pathogens and nematodes are a limitation to the increased uptake of composted organic waste by potential end-users in the horticultural and agricultural sectors. For convenience, in this review eradication is defined as a reduction in the levels of a pathogen to below the limit of detection of the specific 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.

Bollen & Volker (1996) and Ryckeboer (2001) have previously reviewed survival and eradication of plant pathogens and nematodes during composting. The aim of this review is to collate the available data from these and other sources, together with estimated detection limits, so that recommendations for the phytosanitary requirements of composting could be made.

The composting process normally consists of three phases that can be more-or-less distinct: an initial mixing period with mesophilic growth; a high-temperature thermophilic phase (or sanitization); and a longer and lower temperature mesophilic phase (maturation or stabilization) (Day & Shaw, 2001). The success of composting in eliminating pathogens is not solely a result of the heating process, but also depends on the many and complex microbial interactions that may occur, as well as other compost parameters such as moisture content (Bollen, 1985). According to Bollen (1985), the eradication of pathogens from organic wastes during composting is primarily due to: (i) heat generated during the thermophilic phase of the composting process; (ii) the production of toxic compounds such as organic acids and ammonia; (iii) lytic activity of enzymes produced in the

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compost; and (iv) microbial antagonism, including the production of antibiotics and parasitism.

Other factors involved in eradication are: (v) competition for nutrients (Ryckeboer, 2001); (vi) natural loss of viability of the pathogen with time (Coventry *et al*., 2002); and (vii) 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 (Bollen & Volker, 1996). Although pathogen numbers may continue to decline during compost maturation, the conditions are more difficult to define for sanitization standards, and are less likely to be conducive for reliable pathogen eradication than the high-temperature phase. The combinations of temperature and duration of exposure are referred to as temperature–time effects in this review.

Systems used for studying temperature–time effects on eradication

The pathogen and nematode species covered in this review, together with their hosts and the common names of the associated diseases, are listed in Table 1. These are mainly soilborne organisms as these are usually considered to pose the greatest risk in subsequent use of composted materials. Most of this research has been conducted during aerobic composting of organic wastes, although data on pathogen eradication in anaerobic digester liquid, soil, agar, water and plant material with dry heat or steam–air is also shown for comparison. For some organisms (e.g. *Pythium ultimum*), only data obtained in noncomposting systems are available. For tests conducted in compost a range of feedstocks have been used, although the most widely used materials were various crop or plant residues, including 'green' or 'yard' waste (a mixture of leaves, prunings and grass clippings from parks and gardens). Other feedstocks used in eradication tests were municipal organic wastes or 'biowastes' (Menke & Grossmann, 1971; Christensen *et al*., 2001), bark (Hoitink *et al*., 1976) or woodchips (Bruns *et al*., 1993). Some authors included nitrogenous materials or 'activators' such as animal manures (Lopez-Real & Foster, 1985; Dittmer *et al*., 1990) or inorganic nitrogen sources (Hoitink *et al*., 1976; Coventry *et al*., 2001).

Where eradication tests were conducted in compost, these were mostly conducted in self-heating heaps (piles) of varying size, with or without forced aeration or turning. The temperatures within such heaps varied in both space and time. Bollen *et al.* (1989) and Bollen (1993) quote a maximum compost temperature for the heat phase of the tests. During this heat phase, compost temperatures increased from ambient to these maximum values and back down to ≈ 30 °C over a period of 3–4 weeks. The eradication and survival temperatures during composting in Tables 2–9 are the maximum or average values during the specified times, which were normally part or all of the heat phase of the composting test. The composting tests of Coventry *et al.* (2001) were conducted in thermostatically controlled aerated flasks at constant temperature. Where eradication data were obtained in other (noncomposting) test systems (Table 4), the test material was directly exposed to dry heating in an incubator or indirectly heated in a water bath or similar equipment. In these other test systems, the temperatures were generally determined more accurately than in composting systems. The reliability of the data will depend on the accuracy and calibration of the temperature-monitoring equipment, as well as the proximity of the test pathogen to the monitoring probe.

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 3 or more weeks after the start of the test (e.g. Bollen *et al*., 1989) so that a shorter eradication time cannot be specified.

The pathogen inocula for composting tests were normally infected plant materials. These may have contained a single type or a range of types of growth stages or propagules. In some work, the growth stage or propagule used for inoculum is specified (e.g. spores, sclerotia, mycelium). In all the references, the viability of the uncomposted inoculum (positive control treatment) was confirmed with the same procedure used for testing the viability of inoculum retrieved from the compost.

The apparent eradication of a pathogen can be an artefact of the experimental system. In most references only a single population size of test organism was used in eradication tests. Given that the survival time for individual propagules will not be the same for each individual, but will follow some type of statistical distribution for a given set of conditions and detection assay, the apparent survival will vary according to initial population size. For example, Jones (1982) showed that the initial population of *Salmonella* propagules was positively related to the survival rate at different temperatures. Thus variation in the initial populations may (at least partly) explain differences in eradication test results between different authors.

Methods used for assessing survival of plant pathogens and nematodes during composting

In order to assess the survival of plant pathogens in compost, some method for recovering the target pathogen from the composted material is required. In nearly all the papers reviewed, this was achieved by placing inoculum in nylon sacks or some other inert container, which was then withdrawn from the compost either at the end of, or at intervals during, the composting process. Once retrieved, the material was assayed for the presence of the pathogen. The methods used to assay the recovered samples are indicated in Tables 2–9, and included bioassays, direct plating, dilution plating, serological and direct microscopic examination.

Detection limits and reliability

Associated with any assay is a limit of detection (the lowest concentration that can be detected with a reasonable

Table 1 Plant pathogens and nematodes covered in this review, hosts and common name of diseases caused, or of nematodes

Pathogen	Host(s)	Common name of disease or nematode
Fungi		
Armillaria mellea	various woody	honey fungus
Botrytis aclada (syn. *allii*)	onion (*Allium cepa*)	neck rot
Botrytis cinerea	various	grey mould
Colletotrichum coccodes	Solanaceae	anthracnose
Didymella lycopersici	tomato (*Lycopersicon esculentum*)	stem rot
Fusarium oxysporum f.sp. *callistephi*	*Aster* spp.	wilt
F. oxysporum f.sp. *dianthi*	carnation, pink (*Dianthus* spp.)	wilt
F. oxysporum f.sp. *lilii*	lily (*Lilium* spp.)	scale rot
F. oxysporum f.sp. *lycopersici*	tomato (*L. esculentum*)	wilt
F. oxysporum f.sp. *melongenae*	egg plant (*Solanum melongena*)	wilt
F. oxysporum f.sp. *melonis*	melon (*Cucumis melo*)	wilt
F. oxysporum f.sp. *narcissi*	*Narcissus* spp.	basal rot
F. oxysporum f.sp. *pisi*	pea (*Pisum sativum*)	wilt
Fusarium solani f.sp. *cucurbitae*	Cucurbitaceae	wilt
Macrophomina phaseolina	various	dry root rot
Olpidium brassicae	various	vectors of LBVV and TNV
Phomopsis sclerotioides	cucumber (*Cucumis sativus*)	black rot
Pseudocercosporella herpotrichoides	wheat (*Triticum aestivum*)	foot rot
Pyrenochaeta lycopersici	tomato (*L. esculentum*)	corky root
Rhizoctonia solani	various potato black-scurf	damping-off,
Sclerotinia fructigena	stone fruits (*Prunus* spp.)	brown rot
Sclerotinia minor	various	blight
Sclerotinia sclerotiorum	various	watery soft rot
Sclerotium cepivorum	*Allium* spp.	white rot
Sclerotium (*Corticium*) *rolfsii*	various	southern blight
Septoria lycopersici	tomato (*L. esculentum*)	leaf spot
Stromatinia gladioli	*Gladiolus* spp.	dry rot
Synchytrium endobioticum	potato (*Solanum tuberosum*)	wart disease
Taphrina deformans	peach (*Prunus persica*)	leaf curl
Thielaviopsis basicola	various	black root rot
Verticillium albo-atrum	hop (*Humulus lupulus*)	wilt
Verticillium dahliae	various	wilt
Plasmodiophoromycetes		
Plasmodiophora brassicae	Brassicaceae	clubroot
Polymyxa betae	Chenopodiacae	vector of BNYV
Oomycetes		
Phytophthora cinnamomi	various	root rot, dieback
Phytophthora cryptogea	various	collar rot, root rot
Phytophthora infestans	potato (*S. tuberosum*) tomato (*L. esculentum*)	potato blight
Phytophthora ramorum	various woody	sudden oak death
Pythium irregulare	various	root rot
Pythium ultimum	various	damping-off, root rot
Bacteria		
Clavibacter michiganensis		
ssp. *michiganensis*	tomato (*L. esculentum*)	canker
Erwinia amylovora	Rosaceae	fire blight
Erwinia carotovora ssp. *atroseptica*	potato (*S. tuberosum*)	black leg and soft rot
Erwinia carotovora ssp. *carotovora*	various	soft rot
Erwinia chrysanthemi	various	soft rot, blight
Pseudomonas savastanoi		
pv. *phaseolicola*	*Phaseolus* beans	
Ralstonia solanacearum	Solanaceae	bacterial wilt
Viruses (abbreviation)		
Cucumber green mottle mosaic (CGMMV)	cucumber (*Cucumis sativus*)	
Lettuce big vein (LBVV)	lettuce (*Lactuca sativa*)	
Melon necrotic spot	Cucurbitaceae	
Pepper mild mottle	Solanaceae	
Tobacco mosaic (TMV)	various	

Table 1 Continued

Pathogen	Host(s)	Common name of disease or nematode
Tobacco necrosis (TNV)	various	
Tobacco rattle (TRV)	various	
Tomato mosaic (ToMV)	various	
Tomato spotted wilt virus	various	
Nematodes		
Aphelenchoides ritzemabosi	*Chrysanthemum* spp. strawberry (*Fragaria* spp.)	
Globodera pallida	potato (*S. tuberosum*), tomato (*L. esculentum*)	white potato cyst
Globodera rostochiensis	potato (*S. tuberosum*), tomato (*L. esculentum*)	yellow potato cyst
Heterodera schachtii	beet (*Beta vulgaris*)	beet cyst
Meloidogyne chitwoodii	various	root-knot
Meloidogyne hapla	potato (*S. tuberosum*)	northern root-knot
Meloidogyne incognita	beet (*B. vulgaris*)	southern root-knot
Meloidogyne javanica	various	Javanese root-knot
Pratylenchus penetrans	strawberry (*Fragaria* spp.),	meadow

statistical certainty) and/or a limit of quantification (the lowest concentration that can be determined with acceptable precision and accuracy). Assays may also be subject to other errors and variability, and the final results and their interpretation are subject to sampling errors.

In order to assess the reliability and value of negative results from detection assays, it is vital to have some estimate of the detection limits (or analytical sensitivity). In the majority of the papers reviewed, the authors provided no information and did not appear to have considered this aspect of their work. Therefore, wherever possible, an attempt was made to derive estimates for theoretical detection limits based on the information provided in the papers, and these are given in the appropriate tables for a probability of 0·95: a negative result means that 19 times out of 20 the amount of pathogen will be at this value or below. However, in many cases it was impossible to establish meaningful values due to lack of sufficient detail about the assay method or the numbers of test plants.

Detection of fungi, plasmodiophoromycetes and oomycetes

Bioassays

In addition to true fungi, this review includes several plasmodiophoromycetes (*Plasmodiophora brassicae* and *Polymyxa betae*) and oomycetes (*Pythium* and *Phytophthora* spp.). Bioassays were the most commonly used method for the detection of fungal pathogens (Tables 2–4). In these bioassays, susceptible indicator plant species were grown in samples of the test compost in pots. In some cases the test material was mixed or diluted with a quantity of sterile soil or compost containing fertilizers, lime, etc. to ensure satisfactory plant growth and to avoid problems with toxicity of the fresh compost. Seeds of susceptible indicator species were then either sown directly into the compost or compost mix, or young plants were transplanted. Following incubation for periods of up to several weeks, the presence of particular disease symptoms on plants was taken to indicate the presence of the pathogen.

The success of such 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, but there is little evidence that these aspects have been well researched. In the case of *Rhizoctonia solani* (Christensen *et al*., 2001), indicator plants, although infected, did not express symptoms, as demonstrated by a subsequent serological test on the indicator plants. Other subtle details of an assay may also affect the reliability of the results. For example, Lopez-Real & Foster (1985) stored recovered samples at –24°C before assay, but there is no indication of whether or not this could have had an effect on the viability of pathogen propagules.

None of the papers reviewed gave a clear indication of the analytical sensitivity or recovery rate. Detection limits were calculated as the minimum proportion of infected plants that can be detected with a probability of 0·95, on the basis of the numbers of plants evaluated and assuming a binomial model for infection (Roberts *et al*., 1993). These are expressed in Tables 2–9 as '% inf' and necessarily assume that recovery is 100%. Where the proportion of plants infected in the positive control treatments was less than 100%, then the detection limit must be greater than the theoretical minimum and this is indicated by a greater than sign (>) in the tables.

The sensitivity or recovery of soilborne pathogens by bioassays has been reported only occasionally: 10^3 spores g^{-1} peat and 10^6 spores g^{-1} soil for *P. brassicae* (Staniaszek *et al*., 2001) and 1·7% recovery for *P. betae* (Tuitert, 1990).

Table 2 Temperature–time conditions for eradication of plant pathogenic fungi, plasmodiophoromycetes and oomycetes in compost

Pathogen	Inoculum	Feedstock (in heaps unless stated)	Temperature[a] (°C; max unless stated)	Time (days)	Detection			Reference
					Method	Medium	Limit[b]	
Fungi								
Armillaria mellea	cherry wood	garden refuse	70	21	plating	PDA	12% res	Yuen & Raabe (1984)
Botrytis aclada	bulbs/sclerotia	garden refuse	64–70	21	bioassay	onion bulbs	5% inf	Bollen *et al.* (1989)
Botrytis cinerea	bean leaves	grass, hop waste, manure	35	4	bioassay	bean	?	Lopez-Real & Foster (1985)
B. cinerea	geranium stems/leaves	bark	60	91	plating	selective agar	4% res	Hoitink *et al.* (1976)
Colletotrichum coccodes	tomato, aubergine roots/stems	garden refuse	64–70	21	bioassay	aubergine	5% inf	Bollen *et al.* (1989)
Didymella lycopersici	tomato haulms	inoculum	59–73	7	bioassay	tomato	8% inf	Phillips (1959)
Fusarium oxysporum								
f.sp. *callistephi*	Chinese aster	garden refuse	47–65	21	bioassay	Chinese aster	8% inf	Bollen *et al.* (1989)
f.sp. *lilii*	lily bulbs	garden refuse	58–70	21	bioassay	lily bulb scales	> 3% inf	Bollen *et al.* (1989)
f.sp. *melonis*	melon roots/stems	garden refuse	56–67	21	bioassay	melon	4% inf	Bollen *et al.* (1989)
f.sp. *melonis*	melon residue	plant residues	64	4	plating	PDA	?	Suarez-Estrella *et al.* (2003)
f.sp. *narcissi*	bulb peelings	plant residues	40	210	?	?	?	Bollen *et al.* (1991)
Fusarium solani	courgette roots/stems	garden refuse	53–65	21	bioassay	courgette	8% inf	Bollen *et al.* (1989)
f.sp. *cucurbitae*								
Phomopsis sclerotioides	gherkin roots	garden refuse	64–70	21	bioassay	gherkin	> 4% inf	Bollen *et al.* (1989)
Pseudocercosporella herpotricoides	mycelium	green waste, straw	60	7	plating	water agar + antibiotics	?	Dittmer *et al.* (1990)
Pyrenochaeta lycopersici	tomato roots	garden refuse	53–65	21	bioassay	tomato	5% inf	Bollen *et al.* (1989)
Rhizoctonia solani	potato tubers/sclerotia	garden refuse	64–70	21	bioassay	potato	> 13% inf	Bollen *et al.* (1989)
R. solani	millet seed	garden refuse, sawdust	70	21	plating	water agar	12% res	Yuen & Raabe (1984)
R. solani	beet pieces	bark	50	77	bioassay	beet	2% inf	Hoitink *et al.* (1976)
R. solani	wheat kernels	household, various	52 av	49	bioassay + ELISA	bean	> 9% inf	Christensen *et al.* (2001)
Sclerotinia sclerotiorum	lettuce stems/sclerotia	garden refuse	64–70	21	bioassay	cucumber	> 5% inf	Bollen *et al.* (1989)
S. sclerotiorum	sclerotia	green waste, manure	74	23	fluorescence microscope	fluorescein diacetate	5% scler	Dittmer *et al.* (1990)
S. sclerotiorum	sclerotia	biowaste	74	18	plating	PDA	?	Hermann *et al.* (1994)
Sclerotium cepivorum	bulbs/sclerotia	garden refuse	64–70	21	bioassay	onion	> 8% inf	Bollen *et al.* (1989)
S. cepivorum	sclerotia	onion waste (flasks)	48 const	3	plating	PDA	2% scler	Coventry *et al.* (2002)
Sclerotium rolfsii	sclerotia	spice–sawdust	32	12	plating	water agar	2% scler	Yuen & Raabe (1984)

Table 2 Continued

Pathogen	Inoculum	Feedstock (in heaps unless stated)	Temperature[a] (°C; max unless stated)	Time (days)	Detection			Reference
					Method	Medium	Limit[b]	
Stromatinia gladioli	gladiolus leaves/sclerotia	garden refuse	64–70	21	bioassay	gladiolus	2% inf	Bollen *et al.* (1989)
Thielaviopsis basicola	spores	?	63	?	heap	?	?	Grushevoi & Levykh (1940)
Verticillium dahliae	rose stems	garden refuse, sawdust	70	21	plating	cellophane agar	20% res	Yuen & Raabe (1984)
Plasmodiophoromycetes								
Plasmodiophora brassicae	cabbage roots	garden refuse	47–65	21	bioassay	Chinese cabbage	> 8% inf	Bollen *et al.* (1989)
P. brassicae	cabbage roots	grass, hop waste, manure	54 av	1	bioassay	cabbage	?	Lopez-Real & Foster (1985)
P. brassicae	galls/soil	household, woodchips	60–80	49	bioassay	cauliflower	9% inf	Bruns *et al.* (1993)
P. brassicae	galls/soil	household, various	49 av	14	bioassay	*Brassica juncea*	> 7% inf	Christensen *et al.* (2001)
P. brassicae	cauliflower roots/soil	biowaste or green waste	60 av	2	bioassay	*Brassica juncea*	?	Ryckeboer (2001)
Oomycetes								
Phytophthora cinnamomi	rhododendron crown/roots	bark	50	77	baiting + plating	lupin	?	Hoitink *et al.* (1976)
Phytophthora cryptogea	Chinese aster root clods	garden refuse	64–70	21	bioassay	Chinese aster	> 5% inf	Bollen *et al.* (1989)
Phytophthora infestans	potato tubers	garden refuse	47–65	21	bioassay	potato disks	3% inf	Bollen *et al.* (1989)
Phytophthora ramorum	oak wood, laurel leaves	wood chips, green waste	?	14	bioassay	pear	?	Garbelotto (2003)
Pythium irregulare	rhododendron crown/roots	bark	50	77	baiting + plating	lupin	?	Hoitink *et al.* (1976)

[a]Maximum, average or constant temperatures recorded.

[b]Detection limit estimated from experimental details for $P = 0{\cdot}95$ as percentages of test plants infected (% inf), residue samples tested (% res), sclerotia surviving (% scler), or not determined or stated (?).

Table 3 Temperature–time conditions for survival of plant pathogenic fungi and plasmodiophoromycetes in compost

Pathogen	Inoculum	Feedstock (in heaps unless stated)	Temperature[a] (°C, max unless stated)	Time (days)	Detection		Reference
					Method	Medium	
Fungi							
Didymella lycopersici	tomato haulms	inoculum	56	27	bioassay	tomato	Phillips (1959)
Fusarium oxysporum							
f.sp. *lycopersici*	wheat kernels	household, various	74	21	bioassay	tomato	Christensen *et al.* (2001)
f.sp. *melongenae*	aubergine root clods	garden refuse	53–65	21	bioassay	aubergine	Bollen *et al.* (1989)
f.sp. *pisi*	mycelium/soil	onion waste (flasks)	50 const	7	plating[b]	komada	Coventry *et al.* (2001)
Macrophomina phaseolina	infected roots	crop, weed residues	60–62	21	plating	selective agar	Lodha *et al.* (2002)
Olpidium brassicae	lettuce root clods	garden refuse	56–67	21	bioassay[b]	lettuce	Bollen *et al.* (1989)
Rhizoctonia solani	wheat kernels	household, various	57 av	14	bioassay + ELISA	bean	Christensen *et al.* (2001)
Sclerotinia sclerotiorum	sclerotia	green waste, straw	42	23	fluorescence microscope	fluorescein diacetate	Dittmer *et al.* (1990)
Plasmodiophoromycetes							
Plasmodiophora brassicae	naturally present	sludge, manure, feathers	70	175	bioassay	*Brassica nigra*	Ylimaki *et al.* (1983)
P. brassicae	galls, soil	household, woodchips	40–60	98	bioassay	cauliflower	Bruns *et al.* (1993)
P. brassicae	galls, soil	biowaste	60	182	bioassay	*Brassica juncea*	Ryckeboer *et al.* (2002b)

[a]Maximum, average or constant temperatures recorded.
[b]Recorded after the test at values close to the limit of detection.

Table 4 Temperature–time conditions for eradication of plant pathogenic fungi, plasmodiophoromycetes and oomycetes in other systems

Pathogen	Inoculum	Medium	Temp (°C)	Time	System	Detection			Reference
						Method	Medium	Limit[a]	
Fungi									
Armillaria mellea	citrus roots	inoculum	41	7 h	steam–air	direct plating	agar	18% inf	Munnecke *et al.* (1976)
A. mellea	infected plants	inoculum	49	30 min	steam–air	direct plating	agar	18% inf	Munnecke *et al.* (1976)
Botrytis cinerea	geranium stems/leaves	inoculum	40	21 days	incubator	direct plating	PDA, selective agar	5% res	Hoitink *et al.* (1976)
B. cinerea	geranium stems/leaves	inoculum	50	7 days	incubator	direct plating	PDA, selective agar	5% res	Hoitink *et al.* (1976)
B. cinerea	spores	water	47	4 min	water	direct plating	agar	0·25% res	Smith (1923)
B. cinerea	spores	water	50	6 min	water	direct plating	agar	0·25% res	Smith (1923)
B. cinerea	conidia	water	65	10 min	water	bioassay	bean	?	Lopez-Real & Foster (1985)
Fusarium oxysporum	suspension	sewage	35	3 days	anaerobic	enrichment	Czapek Dox and PSA	30 prop/mL	Turner *et al.* (1983)
f.sp. *dianthi*		sludge			digester	plating			
f.sp. *melonis*	melon residues	inoculum	55	4 days	incubator	plating	PDA	?	Suarez-Estrella *et al.* (2003)
Olpidium brassicae	sporangia	water	50	10 min	water bath	bioassay	lettuce	12·5% spora	Campbell & Lin (1976)
Rhizoctonia solani	barley seed	inoculum	40	49 days	incubator	direct plating	PDA and water agar	?	Hoitink *et al.* (1976)
R. solani	barley seed	inoculum	50	7 days	incubator	direct plating	PDA and water agar	?	Hoitink *et al.* (1976)
R. solani	mycelium	water	50	7 min	water	direct plating	PDA	?	Miller & Stoddard (1956)
R. solani	mycelium	agar	50	12 min	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
Sclerotinia fructigena	infected plants	?	52	?	?	?	?	?	Spector (1956)
Sclerotinia minor	sclerotia	soil	50	1·5 days	incubator	direct plating	semiselective	6% scler	Adams (1987)
Sclerotinia sclerotiorum	sclerotia	inoculum	50	39 days	incubator	direct plating	PDA	?	Hermann *et al.* (1994)
S. sclerotiorum	sclerotia	inoculum	70	4 days	incubator	direct plating	PDA	?	Hermann *et al.* (1994)
S. sclerotiorum	sclerotia	soil	60	3 min	steam–air	direct plating	PDA, semiselective	3·5% scler	van Loenen *et al.* (2003)
S. cepivorum	sclerotia	soil	40	8 days	incubator	direct plating	PDA	1% scler	McLean *et al.* (2001)
S. cepivorum	sclerotia	soil	45	12 h	incubator	direct plating	PDA	1% scler	McLean *et al.* (2001)
S. cepivorum	sclerotia	soil	50	6 h	incubator	direct plating	PDA	1% scler	McLean *et al.* (2001)
S. cepivorum	sclerotia	soil	45	1·7 days	incubator	direct plating	semiselective	6% scler	Adams (1987)
S. cepivorum	sclerotia	soil	50	19 h	incubator	direct plating	semiselective	6% scler	Adams (1987)
S. cepivorum	sclerotia	soil	50	3 min	steam–air	direct plating	PDA	2·5% scler	van Loenen *et al.* (2003)
Septoria lycopersici	spores	?	43	?	water	?	?	?	Spector (1956)
Synchytrium endobioticum	sporangia	water	60	8 h	water bath	staining	acid fuchsin	7% spora	Glynne (1926)
Taphrina deformans	mycelium	?	46	?	?	?	?	?	Spector (1956)
Thielaviopsis basicola	mycelium	agar	45	15 h	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
T. basicola	mycelium	agar	50	1·3 min	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
Verticillium albo-atrum	hop vine	inoculum	50	3 h	water bath	direct plating	PLY agar	?	Talboys (1961)

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Table 4 Continued

Pathogen	Inoculum	Medium	Temp (°C)	Time	System	Detection			Reference
						Method	Medium	Limit[a]	
V. albo-atrum	hop vine	inoculum	55	1 h	water bath	direct plating	PLY agar	?	Talboys (1961)
V. albo-atrum	hop vine	inoculum	60	15 min	water bath	direct plating	PLY agar	?	Talboys (1961)
V. albo-atrum	mycelium	water	53	4 min	water bath	direct plating	PDA	?	Miller & Stoddard (1956)
V. albo-atrum	microsclerotia	water	55	4 min	water bath	direct plating	PDA	?	Miller & Stoddard (1956)
V. albo-atrum	mycelium	plant stem	47	5 min	water	direct plating	barley straw agar	?	Nelson & Wilhelm (1958)
V. albo-atrum	microsclerotia	plant stem	47	40 min	water	direct plating	barley straw agar	?	Nelson & Wilhelm (1958)
Verticillium dahliae	mycelium	agar	45	8 h	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
V. dahliae	mycelium	agar	47	2 h	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
V. dahliae	microsclerotia	soil	50	3 min	steam–air	direct plating	selective agar	2·5% res	van Loenen *et al.* (2003)
Plasmodiophoromycetes									
Plasmodiophora brassicae	filtered extract	water	75	10 min	water	bioassay	cabbage	?	Lopez-Real & Foster (1985)
P. brassicae	roots/soil	biowaste	52	10 h	anaerobic digester	bioassay	*Brassica juncea*	25% inf	Ryckeboer *et al.* (2002a)
Oomycetes									
Phytophthora cinnamomi	rhododendron crown/roots	inoculum	40	7 days	incubator	direct plating	selective agar	?	Hoitink *et al.* (1976)
Phytophthora infestans	mycelium	water	45	?	water	?	?	?	Spector (1956)
P. infestans	spores	water	25	?	water	?	?	?	Spector (1956)
Phytophthora ramorum	wood chips/bay leaves	inoculum	55	14 days	incubator	direct plating	selective agar	?	Garbelotto (2003)
Pythium ultimum	infected Aloe plants	water	46	45 min	water	bioassay	*Aloe variegata*	?	Baker & Cummings (1943)
P. ultimum	mycelium	agar	45	9 h	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
P. ultimum	mycelium	agar	50	33 min	water bath	direct plating	PDA	2% res	Pullman *et al.* (1981)
P. ultimum	mycelium	soil	50	3 min	steam–air	bioassay	pea	?	van Loenen *et al.* (2003)
Pythium irregulare	rhododendron crown/roots	inoculum	40	7 days	incubator	baiting + plating	lupin	?	Hoitink *et al.* (1976)

[a]Detection limit estimated from the experimental details for $P = 0{\cdot}95$ as percentages of test plants infected (% inf), residue samples tested (% res), sclerotia or sporangia surviving (% scler or % spora), propagules mL^{-1} (prop mL^{-1}), or not determined or stated (?).

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Table 5 Temperature–time conditions for eradication of bacterial plant pathogens in compost and other systems

Bacterium	Inoculum	Feedstock/ medium	Temp.[a] (°C)	Time	System	Detection			Reference
						Method	Medium	Limit[b]	
In compost									
Erwinia amylovora	cotoneaster shoots	biowaste, woodchips	> 40 max	7 days	heap	dilution plating	M–S	> 300 cfu g^{-1}	Bruns *et al.* (1993)
E. amylovora	suspension	biowaste	55 max	56 h	aerated tunnel	dilution plating	selective	?	Ryckeboer (2001)
Erwinia chrysanthemi	chrysanthemum	bark	60 max	77 days	heap	dilution plating	selective	8% res	Hoitink *et al.* (1976)
Pseudomonas savastanoi pv. *phaseolicola*	bean leaves	grass, hop waste, manure	35 max	4 days	heap	bioassay	bean	?	Lopez-Real & Foster (1985)
Ralstonia solanacearum	potato pieces	biowaste	59 max	16 h	aerated tunnel	dilution plating	selective agar	20 cfu mL^{-1} digest 1E3 cfu g^{-1} infected material	Ryckeboer (2001)
In other systems									
Clavibacter michiganensis ssp. *michiganensis*	suspension	sewage sludge, tomato	35 av	7 days	anaerobic digester	enrichment and dilution plating	D2 broth & nutrient agar	3E3 cfu mL^{-1}	Turner *et al.* (1983
E. amylovora	suspension	inoculum	50 const	30 min	water bath	dilution plating	KB	?	Keck *et al.* (1995)
E. amylovora	apple budwood	inoculum	45[c] const	3 h	incubator	dilution plating	KB	9% inf	Keck *et al.* (1995)
Erwinia carotovora ssp. *atroseptica*	suspension	inoculum	50 const	15 min	water bath	dilution plating	nutrient agar	?	Robinson & Foster (1987)
Erwinia carotovora ssp. *carotovora*	suspension	inoculum	50 const	30 min	water bath	dilution plating	nutrient agar	?	Robinson & Foster (1987)
E. chrysanthemi	suspension	inoculum	50 const	40 min	water bath	dilution plating	nutrient agar	?	Robinson & Foster (1987)
E. chrysanthemi	chrysanthemum	inoculum	40 const	7 days	incubator	dilution plating	selective	10% res	Hoitink *et al.* (1976)
P. savastanoi pv. *phaseolicola*	filtered leaf macerate	inoculum	65 const	10 min	water bath	bioassay	bean	?	Lopez-Real & Foster (1985)
R. solanacearum	suspension	biowaste	52 const	12 h	anaerobic digester	dilution plating	selective agar	20 cfu mL^{-1} digest 1E3 cfu g^{-1} infected material	Ryckeboer *et al.* (2002a)

[a]Maximum, average or constant temperatures recorded.

[b]Detection limit estimated from experimental details for $P = 0{\cdot}95$ as percentages of test plants infected (% inf), residue samples tested (% res), colony-forming units per g or L (cfu g^{-1} or cfu mL^{-1}), or not determined or stated (?).

[c]Survived 50°C for 3 h using moist heat.

Table 6 Temperature–time conditions for eradication of viral plant pathogens in compost and other systems

Virus	Inoculum	Feedstock/ medium	Temp.[a] (°C)	Time (days)	System	Detection			Reference
						Method	Medium	Limit[b]	
In compost									
Cucumber green mottle mosaic	cucumber residue	inoculum	72 max	4	heap	bioassay	cucumber	30%	Avgelis & Manios (1992)
Lettuce big vein/ Olpidium	lettuce	onion waste	50 const	7	flasks	bioassay	lettuce	?	Coventry *et al.* (2002)
Melon necrotic spot	melon plants	horticultural wastes	65 max	28	heap	bioassay/ELISA	melon	?	Suarez-Estrella *et al.* (2002)
Pepper mild mottle	pepper plants	horticultural wastes	65 max	70	heap	bioassay/ELISA	pepper	?	Suarez-Estrella *et al.* (2002)
Tobacco mosaic	tobacco leaves	biowaste	74 max	48	heap	bioassay	tobacco	?	Hermann *et al.* (1994)
Tobacco mosaic	tobacco leaves	biowaste	31 max	184	vessels	bioassay	tobacco	?	Ryckeboer *et al.* (2002b)
Tobacco mosaic	tobacco leaves	household, various	66 av	28	heap	bioassay/ELISA	tobacco	?	Christensen *et al.* (2001)
Tobacco mosaic	tobacco leaves	biowaste	78 max	57	aerated tunnels	bioassay	tobacco	?	Ryckeboer (2001)
Tobacco necrosis	bean leaves	grass, hop waste, manure	54 ave	4	heap	bioassay	bean	?	Lopez-Real & Foster (1985)
Tobacco necrosis/ Olpidium	tulip debris/soil	inoculum	50 av	50	heap	bioassay	tulip	15%	Asjes & Blom-Barnhoorn (2002)
Tomato mosaic	tomato residue	inoculum	46 max	10	heap	bioassay	tobacco	60%	Avgelis & Manios (1989)
Tomato spotted wilt	pepper plants	horticultural wastes	65 max	2·5	heap	bioassay/ELISA	pepper	?	Suarez-Estrella *et al.* (2002)
In other systems									
Cucumber green mottle mosaic	cucumber residue	inoculum	72 const	3	incubator	bioassay	cucumber	30%	Avgelis & Manios (1992)
Tobacco mosaic	plant juice	inoculum	94 const	10 min	water bath	bioassay	tobacco/bean	?	Price (1933)
Tobacco mosaic	plant juice	inoculum	75 const	40	water bath	bioassay	tobacco/bean	?	Price (1933)
Tobacco necrosis	filtered leaf macerate	inoculum	75 const	10 min	water bath	bioassay	bean	?	Lopez-Real & Foster (1985)
Tobacco rattle	?	inoculum	75–80 const	10 min	water bath	?	?	?	Schmelzer (1957)
Tobacco necrosis/ Olpidium	tulip debris/soil	inoculum	50 av	14	incubator	bioassay	tulip	15%	Asjes & Blom-Barnhoorn (2002)

[a]Maximum, average or constant temperatures recorded.
[b]Detection limit estimated from experimental details for $P = 0{\cdot}95$ as percentages of test plants infected or not determined or stated (?).

Table 7 Temperature–time conditions for survival of viral plant pathogens in compost and other systems

Virus	Inoculum	Feedstock/ medium	Temp.[a] (°C)	Time (days)	System	Detection		Reference
						Method	Medium	
In compost								
Cucumber green mottle mosaic	cucumber residue	inoculum	72 max	3	heap	bioassay	cucumber	Avgelis & Manios (1992)
Tobacco rattle	tobacco leaves	refuse	69 max	6	tower	bioassay	tobacco	Menke & Grossmann (1971)
Pepper mild mottle	pepper plants	horticultural wastes	65 max	56	heap	bioassay/ ELISA	pepper	Suarez-Estrella *et al.* (2002)
Tobacco mosaic	tobacco leaves	biowaste	64 max	87	heap	bioassay	tobacco	Hermann *et al.* (1994)
Tobacco mosaic	tobacco leaves	household, various	56 av	28	heap	bioassay	tobacco	Christensen *et al.* (2001)
Tobacco mosaic	tobacco residues	bark	70 max	42	heap	bioassay	tobacco	Hoitink & Fahy (1986)
Tobacco mosaic	tobacco leaves	inoculum	54 max	53	vessels	bioassay	tobacco	Ryckeboer (2001)
Tobacco necrosis	bean leaves	grass, hop waste, manure	54 av	3	heap	bioassay	bean	Lopez-Real & Foster (1985)
In other systems								
Cucumber green mottle mosaic	cucumber residue	inoculum	50 const	30	incubator	bioassay	cucumber	Avgelis & Manios (1992)
Cucumber green mottle mosaic	cucumber residue	inoculum	72 const	2	incubator	bioassay	cucumber	Avgelis & Manios (1992)
Tobacco necrosis	filtered leaf macerate	inoculum	65 const	10 min	water bath	bioassay	bean	Lopez-Real & Foster (1985)
Tomato mosaic	seeds	inoculum	70 const	22	incubator	bioassay	tobacco	Broadbent (1965)
Tomato mosaic	seeds	inoculum	72 const	22	incubator	bioassay	tomato	Howles (1961)
Tobacco mosaic	tobacco leaves	biowaste	68 const	12	anaerobic digester	bioassay	tobacco	Ryckeboer *et al.* (2002a)
Tomato mosaic	tomato residue	inoculum	47 av	70	incubator	bioassay	tobacco	Avgelis & Manios (1989)
Tobacco mosaic	plant juice	inoculum	68 const	70	water bath	bioassay	tobacco/bean	Price (1933)
Tobacco necrosis/ Olpidium	tulip debris/soil	inoculum	40 av	35	incubator	bioassay	tulip	Asjes & Blom-Barnhoorn (2002)

[a]Maximum, average or constant temperatures recorded.

Table 8 Temperature–time conditions for eradication of plant parasitic nematodes in compost and other systems

Nematode	Inoculum	Feedstock	Temp.[a] (°C)	Time	System	Detection			Reference
						Method	Medium	Limit[b]	
In compost									
Globodera rostochiensis	cysts	potatoes	33 const	?	heap	?	?	?	Sprau (1967)
Heterodera schachtii	cysts	biowaste	67 max	62 h	vessels	larval emergence	$ZnCl_2$ soln	4% cyst	Ryckeboer (2001)
Meloidogyne chitwoodii	infected tubers of Scorzonera	biowaste	58 av	42 h	aerated tunnels	bioassay	tomato	?	Ryckeboer (2001)
Meloidogyne incognita	pepper/tomato	refuse	57 av	19 h	compost silo	bioassay	gherkin	9% inf	Menke & Grossmann (1971)
M. incognita	egg sacs	biowaste	74 max	4 days	heap	bioassay	pepper	9% inf	Hermann *et al.* (1994)
M. incognita	egg sacs	biowaste	50 const	30 h	incubator	bioassay	pepper	9% inf	Hermann *et al.* (1994)
In other systems									
Aphelenchoides ritzemabosi	infected bulbs	inoculum	45 const	3 h	water bath	?	?	?	Becker (1974)
Globodera pallida	cysts	soil	50 const	3 min	steam–air	larval emergence	diffusate	7·5% cyst	van Loenen *et al.* (2003)
Globodera rostochiensis	cysts	soil	60 const	3 min	steam–air	larval emergence	diffusate	7·5% cyst	van Loenen *et al.* (2003)
Meloidogyne hapla	strawberry roots	inoculum	49 const	7 min	water bath	bioassay/microscopy	water	30% inf	Goheen & McGrew (1954)
M. hapla	rose roots	inoculum	45·5 const	1 h	water bath	larval emergence	rose	?	Martin (1968)
M. incognita	tomato roots	biowaste	52 const	12 h	anaerobic digester	bioassay	tomato	25% inf	Ryckeboer *et al.* (2002a)
Meloidogyne javanica	potato tubers	inoculum	46 const	2 h	water bath	bioassay	tomato	50% inf	Martin (1968)
M. javanica	potato tubers	inoculum	49 const	1 h	water bath	bioassay	tomato	50% inf	Martin (1968)
Pratylenchus penetrans	strawberry roots	inoculum	46 const	45 min	water bath	microscopy	water	?	Goheen & McGrew (1954)
P. penetrans	strawberry roots	inoculum	49 const	7·5 min	water bath	microscopy	water	?	Goheen & McGrew (1954)

[a]Maximum, average or constant temperatures recorded.

[b]Detection limit estimated from experimental details for $P = 0{\cdot}95$ as percentages of test plants infected (% inf), cyst surviving (% cyst), or not determined or stated (?).

Table 9 Temperature–time conditions for survival of plant-parasitic nematodes in compost and other systems

Nematode	Inoculum	Feedstock	Temp.[a] (°C)	Time	System	Detection		Reference
						Method	Medium	
In compost								
Heterodera schachtii	cysts	biowaste	50 max	40 h	heap	larval emergence	$ZnCl_2$ soln	Rykeboer (2001)
In other systems								
Globodera pallida	cysts	sludge	35 av	10 days	anaerobic digester	larval emergence	diffusate	Turner *et al.* (1983)
Heterodera schachtii	cysts	biowaste	52 const	30 min	anaerobic digester	larval emergence	$ZnCl_2$ soln	Ryckeboer *et al.* (2002a)
Meloidogyne javanica	potato tubers	inoculum	47·5 const	1 h	water bath	bioassay	tomato	Martin (1968)
Meloidogyne hapla	rose roots	inoculum	44·5 const	2 h	water bath	larval emergence	rose	Martin (1968)
M. hapla	rose roots	inoculum	45·5 const	30 min	water bath	larval emergence	rose	Martin (1968)
M. hapla	strawberry roots	inoculum	44 const	1 h	water bath	microscopy	water	Goheen & McGrew (1954)

[a]Maximum, average or constant temperatures recorded.

Plating

Direct plating or dilution plating was used for some of the culturable fungi (Tables 2–4). Pieces of composted plant residue or recovered propagules were placed directly on the surface of agar plates, which were then incubated and observed for outgrowth of mycelium or sporulation. Estimates of detection limits were calculated as the proportion of residue containing viable pathogen or the proportion of propagules remaining viable on the basis of the number of residue pieces/sclerotia/spores evaluated and assuming a binomial model. Agar and potato dextrose agar (PDA) were the most commonly used media, although prune–lactose–yeast (PLY) agar (Talboys, 1961), selective agars, and other plant-based media were also used.

Baiting and plating was used by Hoitink *et al.* (1976) for *Pythium* and *Phytophthora* spp. Lupin seedlings were used as the bait to attract zoospores in a water extract of the soil/compost and after incubation (e.g. overnight) the seedlings were plated on a selective agar medium.

Serological methods

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. However, serological methods such as enzyme-linked immunosorbent assay (ELISA) have been used as a secondary confirmation step following baiting of test plants (Christensen *et al.*, 2001) (Tables 2 and 3).

Detection of bacteria

Bioassays

Bioassays were used to detect bacterial pathogens in only one of the papers examined, where crude extracts of composted material were injected directly into host plants (Lopez-Real & Foster, 1985). Insufficient data were provided to allow estimation of detection limits.

Dilution plating

Dilution plating was the most common method used for bacteria (Table 5). Samples of residue were macerated, then diluted and spread on the surface of selective agar plates. If suitable selective media are available which inhibit the growth of more rapidly growing saprophytes, plating can be a very sensitive method for detection. However, if plating is done on nonselective media the results can be unreliable due to overgrowth of saprophytes masking the presence of the target pathogen. Selective media used in the tests were Miller–Schroth (M-S) (Bruns *et al.*, 1993); D2 broth (Turner *et al.*, 1983), King's medium B, supplemented with cycloheximide (Keck *et al.*, 1995), and a selective agar prepared for *Ralstonia solanacearum* (Ryckeboer *et al.*, 2002a).

Although it is relatively easy to estimate (theoretical) detection limits for dilution plating assays, in most cases insufficient data were provided to allow this. Where theoretical values are given it is likely that the practical sensitivity is poorer due to interference from saprophytes. The data from Hoitink *et al.* (1976) allowed estimation of limits in terms of the proportion of residue assuming 100% recovery.

Detection of viruses

All of the virus pathogens were detected by bioassays (Tables 6 and 7). In most of these bioassays, samples of composted material were suspended in buffer, which was then used for direct inoculation of an indicator plant. In some cases (Avgelis & Manios, 1989) the extract was centrifuged and then resuspended in a smaller volume to increase the virus concentration before inoculation (that is, to increase sensitivity). If the virus is present the indicator plant, often a *Nicotiana* species, produces characteristic symptoms of the virus, usually local lesions, within 7–14 days. The number of lesions can be used to provide a relative estimate of the number of virus particles in the

sample extract. Sometimes (e.g. Ryckeboer *et al*., 2002a) the test extract was applied to one half of a leaf and a positive control (e.g. uncomposted material) was applied to the other half, following the method suggested by Walkey (1991). Some authors (Christensen *et al*., 2001; Suarez-Estrella *et al*., 2002) also performed a secondary ELISA test on extracts of the inoculated leaves to confirm the presence of the virus in inoculated leaves. It was impossible to make meaningful estimates of the detection limits of these assays. Even where other details were provided, the volume of extract applied to the leaves was not recorded or estimated, and the efficiency of extraction was unknown.

Where the virus is transmitted by a vector such as *Olpidium brassicae* (e.g. *Tobacco necrosis virus*, TNV; Asjes & Blom-Barnhoorn, 2002 or *Lettuce big vein virus*, LBVV; Coventry *et al*., 2002), or is considered to survive in debris (e.g. *Cucumber green mottle mosaic virus*, CGMMV; Avgelis & Manios, 1992), the bioassay was performed by planting susceptible hosts into the material in the same way as for soilborne fungal pathogens. In these cases the detection limits were estimated as a proportion of test plants infected, as for the fungi.

A major advantage of bioassays 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.

Detection of nematodes

Survival of nematodes was assessed either by bioassay or by counting the number of larvae or juveniles emerging from eggs or cysts (Tables 8 and 9). The emergence of juveniles was usually stimulated by diffusates or $ZnCl_2$ solution. The bioassays were performed in a similar way to those for soilborne fungi, with indicator plants grown in admixtures of the composted material. Detection limits were therefore estimated as the proportion of test plants infected. Larval emergence counts were done by direct microscopic observation of the number of juveniles or larvae emerging from cysts or eggs. Detection limits were therefore estimated as the proportion of cysts or eggs surviving.

Temperature–time effects on plant pathogens and nematodes

Data on temperature–time effects and other sanitizing factors of composting on the eradication and/or survival of 64 plant pathogens and nematodes was retrieved from 52 publications. Of these species and subspecies or pathovars, 47 were examined in compost and 17 were only examined in plant material (with dry heat or steam–air), soil, agar, water or anaerobic digester liquid. Most workers determined a single temperature and time, or limited combinations of temperature and time, for eradication of plant pathogens during composting or in other systems. Feacham *et al.* (1983) determined the effect of combinations of temperature and time in composting sewage sludge on the eradication of several animal pathogens, including *Salmonella* spp. and *Acaris* nematodes. In their tests, as compost temperature declined from 65 to 40°C, eradication times increased from < 1 h to > 100 h. The effects of multiple combinations of temperature and time on eradication have been examined on only a small number of plant pathogens, and usually in noncomposting systems, e.g. for *P. ultimum*, *Verticillium* spp. and *Thielaviopsis basicola* (Talboys, 1961; Pullman *et al*., 1981). Similarly to the above work on animal pathogens, this work has shown a logarithmic relationship between the time required for eradicating a pathogen and the temperature. More comprehensive data are required before comprehensive temperature–time matrices for the eradication of particular plant pathogens or nematodes from composting feedstocks can be constructed.

Plant pathogens (fungi, oomycetes and plasmodiophoromycetes)

Fungi

Of the 25 fungal pathogens examined in compost, 20 were eradicated and *Fusarium oxysporum* f.sp. *pisi* was reduced to values very close to the detection limit after 7 days in compost at 50°C (Table 3). Lower peak or constant temperatures and/or shorter durations may have been satisfactory for eradication, but they were rarely examined in detail in composting systems. Tests in other, noncomposting systems showed that a further eight fungal pathogens were eradicated by a temperature of 55°C held for 14 days or less, although *Synchytrium endobioticum*, the causal agent of potato wart disease, survived in water at 60°C for 2 h (eradicated after 8 h, Table 4) (Glynne, 1926).

Fusarium oxysporum f.sp. *lycopersici*, the causal agent of tomato wilt, survived a peak compost temperature of at least 65°C (possibly as high as 74°C), and a composting duration of up to 21 days, using infected kernels as inoculum (Christensen *et al*., 2001) (Table 3). *Fusarium oxysporum* f.sp. *melongenae* also survived a 21-day composting period with a peak temperature of 53–65°C. These *F. oxysporum formae speciales* were not examined at constant temperature, or in other systems. Although *F. oxysporum* f.sp. *pisi* survived composting at 50°C for 7 days (Table 3), it was reduced to levels close to the detection limit, and can therefore be assumed to be more temperature-sensitive than the above *formae speciales*. Other *F. oxysporum formae speciales* also appeared to be less temperature-tolerant than *F. oxysporum* f.sp. *lycopersici* when tested by other workers (Tables 2 and 4). *F. oxysporum* f.sp. *narcissi* was eradicated after composting for 7 months, even though compost temperatures did not exceed 40°C (Table 2).

The pathogen that causes dry root rot of beans and other crops in warm climates, *Macrophomina phaseolina*, was also able to survive a peak compost temperature of 60–62°C, and a composting duration of up to 21 days (Lodha *et al*., 2002). Conditions for eradicating this pathogen from compost were not established.

Tests in compost (Table 2) and using dry heat (Table 4) showed that sclerotia of *Sclerotinia sclerotiorum* required peak temperatures of up to 74°C for up to 23 days for eradication. Tests in soil at controlled temperature (van Loenen *et al*., 2003) (Table 4) showed that *S. sclerotiorum* was eradicated at 60°C for 3 min. Sclerotia of *Sclerotinia fructigena*, *Sclerotinia minor*, *Sclerotium cepivorum* and *Sclerotium* (*Corticium*) *rolfsii* were all sensitive to constant temperatures below 55°C in compost or other media (Tables 2 and 4).

Oomycetes

One *Pythium* and four *Phytophthora* species were eradicated in compost heaps that reached peak temperatures of 64–70°C during 21 days, or 50°C during 77 days (Table 2). Tests in noncomposting systems showed that these pathogens, as well as *P. ultimum*, were eradicated by a temperature of 55°C held for 14 days or less (Table 4). Bollen *et al.* (1989) found a very low level of survival of *O. brassicae*, the vector of LBVV and TNV, at composting temperatures of 56–67°C, i.e. one test plant out of 53 had a few viable spores in one of the 20 roots examined (Table 3). Single sporangial isolates of *O. brassicae* were eradicated after 10 min in water at 50°C (Table 4), although there was survival of resting spores in root material (Campbell & Lin, 1976).

Plasmodiophoromycetes

Data obtained for *P. brassicae*, the causal agent of clubroot of *Brassica* spp., were very variable. Lopez-Real & Foster (1985), Bollen *et al.* (1989), and Ryckeboer (2001) found that a peak temperature of 54–60°C and composting duration of 1–21 days eradicated the organism. Christensen *et al.* (2001) eradicated *P. brassicae* by using an average compost temperature of 49°C for 14 days (Table 2). However, Ylimaki *et al.* (1983) and Bruns *et al.* (1993) showed that peak temperatures of 60–80°C and composting durations of 49 days or longer were required for eradication (Tables 2 and 3). Water-bath tests (Table 4) also showed that temperatures over 75°C were required for eradication of *P. brassicae* in filtered suspensions, although the tests were conducted for only 10 min (Lopez-Real & Foster, 1985). Both Bollen *et al.* (1989) and Ryckeboer *et al.* (2002b) demonstrated that *P. brassicae* could survive for long periods at lower temperatures during the maturation phase of composting. Experiments described by Sansford (2003) indicated that *P. betae*, the vector of *Beet necrotic yellow vein virus* (BNYV), was eradicated by a composting temperature of 60°C for 1 day, but there was some survival of spores in soil/water suspensions held at 75°C for 30 min.

Bacterial plant pathogens

There is less published information on the eradication conditions for bacterial plant pathogens compared with that for fungi and viruses, and only four bacterial plant pathogens have been examined in composting systems. All the bacterial plant pathogens in Table 5 could be eradicated by a temperature of 60°C, although some contradictions are apparent. For example, Keck *et al.* (1995) found that *Erwinia amylovora* was eradicated in apple budwood subjected to dry heat for 3 h at 45°C, but not when subjected to moist heat at 50°C for the same period. This result is odd because bacteria are usually killed more effectively by moist heat than dry heat (e.g. Turner, 2002). It is possible that such contradictions are entirely due to the limited numbers of experimental units examined in the experiments, (e.g. 35 experimental units give a reliable detection limit of approximately 9%).

The regrowth of *Salmonella* spp. in compost is possible in some circumstances (Russ & Yanko, 1981; Burge *et al*., 1987). The risks of regrowth of bacterial plant pathogens in composted plant debris have not been examined.

Viral plant pathogens

Bartels (1955) reviewed and Walkey & Freeman (1977) examined the inactivation by heat of a range of viruses in plant material that survived the heat treatment. However, this information cannot be extrapolated to the composting situation, as living plant tissue may have an independent effect on viral inactivation.

Coventry *et al.* (2002) and Asjes & Blom-Barnhoorn (2002) showed the infectivity of the LBVV/*Olpidium* and TNV/*Olpidium* complexes was eliminated by composting at 50°C for 7 and 50 days, respectively (Table 6). *Melon necrotic spot virus*, TNV and *Tomato spotted wilt virus* could be eradicated by a peak composting temperature of 65°C and a composting duration of up to 28 days (Table 6). CGMMV, *Pepper mild mottle virus*, *Tobacco mosaic virus* (TMV) and *Tobacco rattle virus* were more temperature-tolerant (Tables 6 and 7). Eradication conditions for TMV were variable, but Price (1933); Hoitink & Fahy (1986); Hermann *et al.* (1994) and Christensen *et al.* (2001) found that peak temperatures over 66°C and composting periods of longer than 28 days were needed. Ryckeboer (2001) also found that a peak compost temperature of 78°C and duration of 57 days was required for eradication, but TMV did not survive after a long period in compost (26 weeks), even at low temperature (31°C) (Table 6). 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* (TomMV), which remained viable in tomato seeds after heating at 70°C in an incubator for more than 20 days (Broadbent, 1965; Howles, 1961), but was inactivated in composted tomato plants after 10 days with a maximum temperature of 46°C (Avgelis & Manios, 1989). However, it should be noted that the detection limit in the latter work was poor.

Infected seeds in compost may be a possible source of TMV and TomMV inoculum. 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 became soft and were

no longer viable after exposure to a compost temperature of 60°C for 10 days.

Plant pathogenic nematodes

All of the nematode species in Table 8 were eradicated by a constant or average compost temperature of 60°C, and a composting duration of < 2 days, with the exception of beet cyst nematode (*Heterodera schachtii*). The cysts had the ability to survive in compost for up to 6 months of the maturation phase (Ryckeboer *et al*., 2002b), but were readily killed during the sanitization phase (Table 8). The root knot nematode *Heterodera marioni* (possibly a synonym of *Meloidogyne hapla*) declined markedly during a 20-week period when decomposing plant waste was added to soil containing galls, but there was no decline of viable galls in the soil alone, although temperatures did not exceed 27°C (Linford *et al*., 1938). This indicates that microbial antagonism and/or degradation of the host plant material are important in the eradication of plant parasitic nematodes from decomposing plant wastes.

Insect pests, such as the larvae of Narcissus bulb fly (*Merodon equestris*) and mushroom cecid fly (*Heteropeza pygmaea*) are sensitive to a temperature of 45°C (Becker, 1974; Fletcher *et al*., 1989). Coventry *et al.* (2001) found that onion fly larvae (*Delia antiqua*) were eradicated from onion waste by composting at 50°C for 1 day (lower temperatures and shorter times were not examined).

Other compost factors involved in pathogen eradication

The moisture content of the organic waste can influence the temperature tolerance of microorganisms, 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 & Volker, 1996). These workers recommended a minimum compost moisture content of 40%. However, the effect of compost moisture on the thermal sensitivity of plant pathogens has not been studied in detail.

The pH may influence pathogen survival if composting conditions are very acidic or alkaline, but this is unlikely to occur under normal composting conditions (Christensen *et al*., 2002). In reviews by Bartels (1956) and Hermann *et al.* (1994), pH values between 3 and 8 did not inactivate *S. sclerotiorum* or TMV, and values between 5·5 and 8 did not inactivate nematodes.

It is known that some mycelial plant pathogens (e.g. *Phytophthora cinnamomi*, *S. rolfsii*) are killed after exposure to relatively high concentrations of ammonia (Henis & Chet, 1968; Gilpatrick, 1969). In the first stages of composting crop residues rich in nitrogen, ammonia probably contributes to sanitization (Bollen & Volker, 1996). Toxic products formed under anaerobic conditions, such as organic acids, may affect pathogens during composting (Bollen & Volker, 1996). Ryckeboer *et al.* (2002a) found that *P. brassicae* was sensitive to temperature in anaerobic digester liquid (Table 4), whereas this organism was temperature-tolerant under aerobic composting conditions (Table 3).

The temperature required to eradicate *Escherichia coli* depended on the composting feedstocks used (Turner, 2002). Differences in moisture or ammoniacal nitrogen did not account for these differences in eradication temperature, although eradication was improved by higher moisture content within a particular feedstock. There is little information on the independent effect of composting feedstocks on the eradication of plant pathogens. The improved eradication of *S. sclerotiorum* in heaps of composting green waste/manure compared with that in heaps of green waste/straw is consistent with the higher temperatures achieved in the former (Dittmer *et al*., 1990).

The microbial degradation of infected plant material in compost has already been mentioned. Microbial antagonism is one of the principal factors involved in disease suppressive properties of compost (Hoitink & Boehm, 1999). However, the role of microbial antagonism in the destruction of pathogens in compost heaps has not been established experimentally (Bollen & Volker, 1996).

Temperature profiling of commercial composting systems

The following are listed by Rynk & Richard (2001) as the main categories of composting system: (i) turned windrows; (ii) passively aerated static piles; (iii) forced aerated static piles; (iv) combined turned and forced aerated windrows; (v) in-vessel systems (horizontal agitated beds, aerated containers or 'tunnels', aerated-agitated containers, silo or tower reactors).

The effectiveness of different composting systems in reducing the pathogen content of the compost products has been examined by de Bertoldi *et al.* (1988); Stentiford (1996); Christensen *et al.* (2001, 2002). This work has shown that maintaining adequate aeration to provide oxygen for thermophilic microorganisms, without hyperventilation, is important in achieving sufficiently high temperatures for sanitization of compost. In turned windrows without aeration, the interior of the stack becomes depleted of oxygen soon after turning (Day & Shaw, 2001), and 10–20% of the composting mass may become anaerobic (Miller *et al*., 1991). Standards for compost sanitization have been developed in the USA by the Composting Council of the United States (Leege & Thompson, 1997), in the UK jointly by the Waste and Resources Action Programme (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: 70°C for 2 days or 65°C for 4 days, with at least five turnings in windrow systems.

Most references referring to temperature during composting show mean or maximum temperatures achieved. However, of critical importance for pathogen eradication is the proportion of the compost that remains below the specified sanitization standards. This will depend on the composting system, its management, the ambient temperatures, and the quantity and type of feedstocks used. Much of the previous work on temperature profiling of composting systems relates to the eradication of animal pathogens, and has been conducted with compost activators such as sewage sludge or animal manures. Of greater relevance to the eradication of plant pathogens are temperature profiles of composting plant residues that may be low in available nitrogen and other nutrients.

Temperatures above 60°C were achieved in all the composting tests in Table 2, except with hardwood bark waste with inorganic fertilizer (Hoitink *et al.*, 1976), spice–sawdust mix (Yuen & Raabe, 1984), green waste mixed with straw (Dittmer *et al.*, 1990), and bulb peelings waste (Bollen *et al.*, 1991). There were often compost temperature ranges of 20°C or higher within composting systems. However, probability studies (Gale, 2002) have shown that the risk of pathogen survival in windrow systems is small, provided 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 static and in-vessel composting systems where there is no or little turning. Data sets analysed by Gale (2002) indicate that, of the composting green waste in turned-windrow and in-vessel systems, at least 20 and 5%, respectively, is below 55°C at any particular time. However, measurements by Christensen *et al.* (2001, 2002) show that there are significant differences in spatial and temporal temperature profiles between different windrow and in-vessel composting facilities. Further work is needed to determine whether the eradication conditions for temperature-tolerant plant pathogens such as *P. brassicae* and some *F. oxysporum formae speciales* can be achieved consistently in different composting systems using plant-based feedstocks.

Conclusions

- Bioassays were the most frequently used methods for the detection of plant pathogenic fungi, oomycetes and viruses, whereas dilution plating was most frequently used for bacterial pathogens.
- It is clear that the detection limits in most studies were quite poor, with infection levels of up to 5% likely to be undetected regularly, and this may explain the variable or inconsistent results obtained for some pathogens by different authors. In most cases it is therefore difficult to determine the value of the results in terms of a quantitative assessment of the risk of using composted wastes for crop production, especially where many thousands of plants could be grown in a batch of compost.
- Experimental designs and detection assays should consider the likely end-user requirements in terms of acceptable infection risk. In current horticultural practice, even 1% primary infection is likely to be unacceptable, and this detection limit was not achieved in any of the composting studies. An essential part of any further work on the eradication of plant pathogens in compost should be to determine the practical recovery and detection limits of the assay used.
- The temperature–time eradication conditions of 64 plant pathogen and nematode species have been retrieved from the literature. For 27 out of 32 pathogenic fungi, all six oomycetes, seven bacterial pathogens and nine nematodes, and three out of nine plant viruses, a peak temperature of 64–70°C and duration of 21 days were sufficient to reduce numbers to below, or very close to, the detection limits of the tests used. In many of the references, the temperatures and times required for eradication have not been determined precisely. Shorter periods and/or lower temperatures may therefore be satisfactory.
- The fungal pathogens *F. oxysporum* f.sp. *lycopersici* (tomato wilt) and *M. phaseolina* (dry root rot) and the clubroot pathogen *P. brassicae* were more temperature-tolerant as they survived a peak compost temperature of at least 62°C (maximum 74°C) and a composting duration of 21 days. The plasmodiophoromycete *P. betae* was eradicated by this treatment, but survived in soil/water at 75°C for 30 min. The fungal pathogen *S. endobioticum* (potato wart disease) survived in water at 60°C for 2 h (eradicated after 8 h), but was not examined in compost.
- Several plant viruses were temperature-tolerant. These were CGMMV, *Pepper mild mottle virus*, *Tobacco rattle virus*, ToMV and TMV. TMV requires a peak compost temperature in excess of 68°C and a composting period longer than 20 days for eradication. However, TMV is degraded in compost over time, and can be eradicated after a composting period of 26 weeks, even at low temperature (31°C). ToMV in infected seeds can withstand over 70°C in an incubator for over 20 days.
- There are insufficient data to produce comprehensive temperature–time matrices for the eradication of particular plant pathogens during composting, as has been achieved for some animal pathogens.
- Maximum compost temperatures above 60°C were achieved in different composting systems with a wide range of feedstocks. However, there were often compost temperature ranges of 20°C or higher within composting systems. This is of particular importance in static or enclosed in-vessel systems where there is no turning of the wastes, and sanitization may be incomplete.

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