
Supplement to final report

A consideration of the PAS110:2010 pasteurisation requirements, and possible alternatives

PAS 110:2010

Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials



This report examines the impact of pasteurisation on a range of common crop pests and diseases, and explores possible alternatives to the current PAS110 approach. It is of specific relevance to AD facilities accepting crop residues and other plant material for processing, although the principles discussed may also be relevant to AD facilities considering alternative transformation approaches in compliance with the Animal By-Products Regulations

WRAP's vision is a world without waste,
where resources are used sustainably.

We work with businesses, individuals and
communities to help them reap the
benefits of reducing waste, developing
sustainable products and using resources
in an efficient way.

Find out more at www.wrap.org.uk

Written by: Richard Thwaites^a, Christine Henry^a, Jeff Peters^a, John Elphinstone^a, Nigel Cook^a, Phil Jennings^a, Susan MacDonald^a, Tom Prior^a, Peter Reed^a, Matthew Smyth^b, Nigel Horan^b and Ralph Noble^c.

^aThe Food and Environment Research Agency (Fera), Sand Hutton, York YO41 1LZ

^bAqua Enviro Ltd, Unit 8 Appleton Court, Calder Park, Wakefield WF2 7AR

^cEast Malling Research, New Road, East Malling, Kent ME19 6BJ

While we have tried to make sure this report is accurate, we cannot accept responsibility or be held legally responsible for any loss or damage arising out of or in connection with this information being inaccurate, incomplete or misleading. This material is copyrighted. You can copy it free of charge as long as the material is accurate and not used in a misleading context. You must identify the source of the material and acknowledge our copyright. You must not use material to endorse or suggest we have endorsed a commercial product or service. For more details please see our terms and conditions on our website at www.wrap.org.uk

Executive summary

The BSI PAS 110 specification ('PAS110') for digestate sets out to ensure that AD input materials (feedstocks) are processed sufficiently so that the resulting digestate presents acceptably low risk to humans, animals, crops or the wider environment. Although it makes reference to plant health, it does not specify any plant pathogens for specific monitoring and assumes that a pasteurisation step of 70°C for one hour is adequate to reduce risks to plant health satisfactorily. However, the evidence to support this approach has not been fully explored in the UK context, particularly for some of the plant pathogens of highest risk, for example organisms likely to occur on common food waste derived feedstocks, such as potatoes. Moreover there are relatively few data to indicate whether potential alternative pathogen kill processes can be considered equivalent to pasteurisation at 70°C for one hour for removal of plant pathogen hazards.

This report examines the impact of pasteurisation on a range of common crop pests and diseases, and explores possible alternatives to the current PAS110 approach. It is of specific relevance to AD facilities accepting crop residues and other plant material for processing, although the principles discussed may also be relevant to AD facilities considering alternative transformation approaches in compliance with the Animal By-Products Regulations.

Experimental evidence on the impacts of mesophilic anaerobic digestion and pasteurisation at different temperatures on a range of crop pests and diseases is presented in detail within our main report for WRAP project OMK002-007. This evidence indicates that a pasteurisation step of 70°C for one hour was sufficient to inactivate most pathogens tested, with some *Phytophthora* and *Fusarium* species being inactivated within one hour at 57°C. Some pathogens (notably *Spongospora subterranea*) were more persistent: viable cells of these pathogens were recovered after pasteurisation, although they were eventually inactivated during subsequent anaerobic digestion at mesophilic temperatures.

This suggests that a combination of pasteurisation and anaerobic digestion is required for elimination of some plant pathogens. Since it is possible that continuous or semi-continuous AD systems will allow pathogens to bypass the reductive effects of digestion our data support the retention of a discrete pasteurisation step in the PAS110 specification, although recognise the importance to industry of flexibility in pasteurisation approach.

In recommending alternatives to pasteurisation it is important to establish equivalence in terms of ability to reduce pathogen risk to an acceptable level. Since all digesters differ in operating parameters (for example: temperature, retention time, vessel design) and, crucially – feedstock – we are unable to recommend a pre-defined set of digestion parameters to obtain equivalence to pasteurisation, since these may not be equally effective across all digester types.

Whilst other authors have proposed a number of pre-defined pasteurisation parameters, these are not proven for the wide range of potential crop pests and diseases that could be associated with some feedstocks (albeit at low levels), and they also require adherence to minimum hydraulic retention times within the digestion phase – which would reduce the flexibility of PAS110. Instead, we propose a validation process by which operators can demonstrate that their process, operated by their personnel, is sufficiently effective at reducing plant pathogen risk. This validation approach has the advantage of being in harmony with the approach taken in implementing Animal By-Products Regulations' requirements for demonstrating equivalence in pasteurisation (or 'transformation') processes that are intended to reduce animal pathogens to acceptable levels.

For validation we propose that any suggested alternative to the standard 70°C for one hour pasteurisation approach be tested for its ability to achieve a defined level of kill of indicator organisms introduced into the pasteurisation system. To aid analysis we propose that these organisms are introduced in sealed containers for ease of recovery and subsequent analysis, and because inoculating an entire reactor with a detectable level of indicator organism would not be practicable. Having considered various options, including those required by the German Biowaste Ordinance, we suggest that relatively persistent organisms for which viability assays can be conducted are chosen as indicators, and for this reason propose *Plasmodiophora brassicae* and tomato seed.

Contents

1.0	Introduction	3
1.1	Current pasteurisation approaches in PAS110	4
2.0	Is the current PAS110 approach suitable for management of phytohygienic hazards?	5
2.1	First principles: Common AD feedstocks and potentially associated phytohygienic hazards	5
2.1.1	Common AD feedstocks	5
2.1.2	Phytohygienic hazards potentially associated with common AD feedstocks, and their potential survival during AD	6
2.1.3	Synthesizing hazards: Is a pasteurisation step needed?	6
3.0	Alternative approaches for phytohygiene management	14
3.1	Controlling digestate phytohygiene in other EU countries	14
3.1.1	Germany	14
3.1.2	Sweden	14
3.1.3	Proposed pan-European approach	14
3.2	Ability to test for pathogens in digestate or feedstock (the 'continuous surveillance' option)	15
3.3	Enhanced Enzymic Hydrolysis (EEH)	15
3.4	The use of indicator organisms	17
3.4.1	Setting alternative processing parameters within the ABPR	17
3.4.2	Possible approaches for non-ABP inputs	17
3.5	Effects of various time-temperature regimes on pathogen eradication	18
3.6	Difficulties with transposing time-temperature regimes for pasteurisation equivalence in AD from other treatment systems	19
3.7	The food industry approach to pasteurisation	20
3.7.1	Pasteurising milk	20
3.7.2	Pasteurising egg	21
3.7.3	Pasteurisation Units	21
3.8	Energy implications of different time/temperature approaches	21
4.0	An alternative phytohygiene control approach for the UK?	22
4.1	Introduction	22
4.2	Exemption of specific feedstocks from a pasteurisation requirement	22
4.3	Use of alternative time/temperature regimes	22
4.4	Restriction of high risk feedstocks	23
4.5	Process-specific validation	23
4.5.1	Validation protocol	23
5.0	References	25
	Appendix 1	30

1.0 Introduction

The voluntary BSI PAS 110:2010 specification (PAS110) currently requires that all compliant AD processes include a pasteurisation phase, with the following exception:

Digested materials made only from manure, unprocessed crops, processed crops, crop residues, glycerol, and/or used animal bedding that arise within the producer's premises or holding and that are used entirely within the same premises or holding are exempt from the pasteurization step (BSI 2010).

This approach applies to processes whether they are accepting Animal By-Product (ABP) inputs – for which there are statutory pasteurisation (or 'transformation') requirements – or plant-based inputs, for which there are no statutory pasteurisation requirements.

Pasteurisation is designed to minimise the risks from microbiological hazards, and once validated with test organisms to demonstrate the required reductive effect on suitably robust test organisms, then it is not necessary to actually demonstrate the extent of pathogen kill during the subsequent operation of the process. The degree of hygienic control afforded by pasteurisation is seen as favourable by stakeholders with an interest in (and an influence upon) the digestate market, for example food retailers. However, the capital and operational costs of pasteurisation can be significant, and there is interest amongst AD operators around whether the near universal pasteurisation requirement in PAS110 can be amended for certain feedstocks without compromising the quality and safety of the resulting digestate.

Alternatives could include:

- Exemptions for certain feedstocks for which risk assessments informed by experimental evidence indicate a minimal microbiological hazard;
- Allowing the use of alternative sanitisation procedures (a comparable derogation system is offered as an option for operators processing animal by-products). This would entail a validation process to ensure that whichever procedure is adopted is sufficient to reduce biological hazards to acceptable levels;
- Operating AD systems under conditions that are themselves demonstrably equivalent to pasteurisation in reducing microbiological hazards. A thermophilic AD (TAnD) system might be able to offer such equivalence, although this would still need to be demonstrated through the use of a validation approach.

For prescribed feedstocks to be exempt, risk assessments must be informed by experimental evidence demonstrating that any relevant microbiological hazard they contain will be subjected to the required level of kill (as determined by a measurable \log_{10} reduction) during whichever AD conditions they are exposed to. The fundamental design of the AD system must also be considered. For example, whilst Mesophilic Anaerobic Digestion (MAD) is known to eliminate *Fusarium* spp. at temperatures around 37°C, conventional 'fill and draw' MAD vessels could allow *Fusarium*-contaminated maize to by-pass the active MAD phase and enter the digestate. Specific control barriers before or after the MAD phase (for example, pasteurisation) completely eliminate the potential for such operational by-pass. In contrast, some feedstocks may already be deemed microbiologically safe for other purposes, particularly those that have been produced under hygiene requirements for human foodstuffs.

Alternative sanitisation procedures carried out in addition to digestion may include an aerobic phase such as composting, which brings the benefit that the microbiological safety of compost has been extensively researched (Noble and Roberts 2004; Noble *et al.* 2009, 2011). Other alternatives include stabilisation by chemical or physical means, such as the liming sometimes used for sewage sludge cake during which a change in pH and temperature (due to exothermic hydrolysis of lime) inactivates microbes.

Where the AD conditions alone can be considered sufficient to kill pathogens, and where this is backed up by experimental evidence, a case can be made that an operating protocol is considered substantially equivalent to pasteurisation. If this approach is adopted then it will be necessary to prescribe a monitoring method such that operators can ensure that required conditions are always met and are able to demonstrate this to bodies accrediting the PAS110.

1.1 Current pasteurisation approaches in PAS110

PAS110 approaches control of human pathogens and animal pathogens by requiring that indicator organisms should be reduced to acceptable levels, e.g. *Salmonella* must be absent in 25 g fresh matter. Unless AD facilities are farm-fed and generate, digest and apply the resulting digestate within the same holding, then those facilities must include a pasteurisation step in the overall AD process. Pasteurisation may take place before or after the digestion phase, and a number of options for time and temperature regimes are provided in the PAS.

These options have been transposed directly from the Animal By-Products Regulations (ABPR) requirements (EU Implementing Legislation 142/2011), see Table 1-1.

Table 1-1 UK and EU alternative time/temperature/particle size regimes for pasteurisation within the Animal By-Products Regulations (and PAS110)

System	UK A*	UK B*	EU
Maximum particle size (mm)	50	60	12
Minimum temperature (°C)	57	70	70
Minimum time spent at minimum temperature (hours)	5	1	1

*Applies to catering waste only, and must be followed by minimum 18 days storage

Under the ABPR, the EU pasteurisation approach is compulsory for all systems accepting low-risk ABP for digestion. However, the European regulation allows Member States to adopt alternative standard approaches for systems that are only accepting catering waste. The two UK alternatives are illustrated in Table 1-1. The regulations also allow AD operators to adopt any kind of pasteurisation approach (or 'transformation' approach, to use the terminology of the regulations), so long as it has been validated using specified test organisms.

PAS110 operators processing only non-ABP inputs may also adopt alternative time/temperature/particle size regimes – provided that such regimes have previously been approved by Animal Health / Veterinary Laboratories Agency (AHVLA) for treatment of ABP inputs.

Whilst these options might appear overly-prescriptive, they do allow operators the maximum flexibility in how they manage other aspects of their process. For example, in contrast with approaches adopted elsewhere in Europe (see below) PAS110 includes no minimum retention period for the active digestion phase(s).

Questions around whether pasteurisation is required for AD processes accepting only non-ABP feedstocks, and the potential for alternative phytohygiene control methods are examined in this report.

2.0 Is the current PAS110 approach suitable for management of phytohygienic hazards?

2.1 First principles: Common AD feedstocks and potentially associated phytohygienic hazards

2.1.1 Common AD feedstocks

Here we consider feedstocks not containing material that falls under the definition of animal by-products (ABP). Anaerobic digestion of ABP material requires a pasteurisation step and subsequent testing for indicator bacteria under statute. There are currently no equivalent statutory controls over the use of non-ABP inputs (unless they are known to contain pathogens with designated quarantine status).

Non-ABP feedstocks for AD could be derived from a range of sources, including source-segregated household biowastes, source-segregated biowastes from commercial and industrial businesses, together with biowastes and 'non-wastes' from agricultural and associated activities (these could include vegetable offcuts from packing plants). Table 2-1 gives a summary of the range of non-ABP materials which may be present in AD feedstocks in the UK. Livestock manures and slurries are not included here, since they are considered an animal by-product¹.

Table 2-1 Plant waste materials typically used as feedstocks for AD

Source	Type of waste plant material
Primary food production and fresh retail waste	Fresh strawberries, raspberries, lettuce, tomatoes, apples, onions, potatoes, peas, beans, broccoli, avocado, citrus fruits, bananas etc
Food processing waste, food washing waste	Coffee, fruit, vegetables, tobacco, tea. Process water and food washing waste
Wastes from washing, cleaning and mechanical reduction of raw materials	Spent grains, fruit and potato pulp Materials unsuitable for consumption or processing Brewing waste – Malt husks, malt sprouts, malt dust
Wastes from forestry	Tree leaves, wood chips etc
Garden waste	Hedge and tree trimmings, grass cuttings and leafy materials
Animal husbandry wastes- farms, stables etc	Old Straw Husks, cereal dust, waste animal feeds Maize and grass silage, fodder beet

In addition to the materials described above, there is increasing interest in the use of crops grown specifically for anaerobic digestion ('purpose-grown crops' or PGCs). Grass, forage maize and forage wheat are often cited as potential PGCs (ADAS/AEA, 2011), and the fate of common pathogens associated with such materials during anaerobic digestion should also be considered – to ensure that appropriate phytohygiene controls are in place.

¹ It should be noted that, if the only ABPs that are used are manure, digestive tract contents, milk, milk based products and colostrum, then no pasteurisation or AHVLA approval is required (AHVLA 2012). However, this material could still be captured by the PAS110 pasteurisation requirements (Section 1.0)

2.1.2 *Phytohygienic hazards potentially associated with common AD feedstocks, and their potential survival during AD*

Lists of pathogens that could *potentially* be found in the range of feedstocks described in the Section 2.1.1 are very large. A list has been collated from current EU and EPPO lists for quarantine pathogens and reviews of UK pathogens (e.g. Noble *et al.* 2011), encompassing pathogens and pests likely to be of interest to the UK in terms of the economic, trade, agricultural and environmental damage that could be caused if a severe infection of an indigenous pest or a new outbreak of a quarantine pest were to occur (see Table 2-2).

2.1.3 *Synthesizing hazards: Is a pasteurisation step needed?*

There are a number of organisms listed in Table 2-2 that are likely to be able to survive AD processes that do not include a pasteurisation stage, and may also be able to subsequently initiate a successful infection. The main categories of such organisms are those with hardy resting spores, e.g. *Spongospora*, clubroot, *Polymyxa betae*, *Synchytrium endobioticum*, *Tilletia indica*, *Verticillium dahliae* and subsp., and some of the more temperature resistant viruses, e.g. *TMV*, *Pepino mosaic potexvirus*, etc. Although some of these organisms are not indigenous to the UK and are therefore unlikely to be found in feedstocks, others are indigenous. For these organisms it is important not to spread these further or increase the background levels of inocula present in agricultural fields.

In the case of fill-and-draw AD systems, there is a possibility that these hazards could by-pass the MAD or TAD stage, and this would increase the number of potential phytohygienic hazards to include some of the bacteria, nematodes and less resilient fungi.

The experimental studies (presented in detail in an accompanying report, with key summary data reproduced in Table 2-2 below) have confirmed that pasteurisation for 1 hour at 70°C eliminates the majority of the organisms of interest. Therefore the 'unavoidable control barrier' that a discrete pasteurisation step provides would be desirable in these circumstances. A possible exception to this would be where systems are fed from and provide digestate back to the same local holding.

Table 2-2 Evidence for survival of organisms through AD processes (without pasteurisation, unless stated). Experimental evidence is presented in the accompanying report for WRAP project OMK002-007, whilst the expert opinions are those of the authors. MAD operating temperature = 37°C; TAD operating temperature = 57°C

Group	Pathogen	Disease	Host	From scientific literature – main points only	Experimental evidence	Expert view
Bacteria	<i>Xanthomonas axonopodis</i> pv. <i>citri</i>	Citrus canker	Citrus			Very low risk
	<i>Ralstonia (Pseudomonas) solanacearum</i> races 3 biovar 2	Brown rot	Potato	<i>R. solanacearum</i> was shown to survive MAD for more than 20 days although Ryckeboer <i>et al.</i> (2002) demonstrated that it could be destroyed to below detectable limits within one day during TAD of source separated household wastes at 52°C	Survives up to 8 days in MAD Eliminated by 1 hour at 70°C	Low risk
	<i>Clavibacter michiganensis</i> subsp. <i>sepedonicus</i>	Ring rot	Potato	Kaemmerer (2009) found thermosensitivity of <i>Cms</i> in AD rose considerably at temperatures above 35°C with a log ₁₀ decrease in population over 10 minutes for every 8°C increase in temperature between 35-55°C. Seigner <i>et al.</i> , (2010) showed that <i>Cms</i> in homogenized naturally infected potato tubers remained viable after 6 hours retention during experimental AD at 37°C with cattle slurry.	Survives up to 8 days in MAD Eliminated by 1 hour at 70°C	Low risk
	<i>Erwinia amylovora</i>	Fireblight	Apple			Low risk
	<i>Acidovorax avenae</i> var. <i>cittuli</i>	Bacterial fruit blotch	Melon			Low risk

	<i>Xanthomonas campestris</i> pv. <i>campestris</i> (strains overcoming napus resistance)	Black rot of crucifers	Oilseed rape			Low risk
	<i>Erwinia carotovora</i> subsp. <i>atroseptica</i> / <i>carotovora</i>	Potato blackleg disease	Potato, Tomato			Medium risk
	<i>Streptomyces scabies</i>				Survives 12 days in MAD and 1 hour at 70°C but this is based on DNA PCR	
Mycoplasmas	<i>Flavescence dorée</i> / vector <i>Scaphoideus titanus</i>	Leafhopper	Grapevine			Low to no risk
Fungi	<i>Claviceps purpurea</i> + ergot toxin, ergotpeptine	Ergot	Rice and other small grain cereals			Low risk
	<i>Chrysomyxa arctostaphyli</i>	Spruce broom rust	Spruce			No risk
	<i>Leptosphaeria maculans</i> (new strains)	Black leg of crucifers	Oilseed rape			Low risk
	<i>Fusarium oxysporum</i> f.sp. <i>pisi</i>	Fusarium wilt	Pea			Low-medium risk
	<i>Fusarium culmorum</i>				Survives 1 day in MAD and 1 hour in TAD	
	<i>Fusarium oxysporum</i>				Survives 1 day in MAD and 1 hour in TAD	
	<i>Fusarium radialis lycopersicae</i>				Survives 1 day in MAD and 1 hour in TAD	
	<i>Helminthosporium oryzae</i>	Rice brown-spot	Rice			No risk
	<i>Magnaporthe grisea</i> / <i>Pyricularia oryzae</i>	Rice blast	Rice			No risk
<i>Ustilago maydis</i>	Corn smut	Maize			Low risk	

	<i>Xanthomonas axonopodis</i> f.sp. <i>allii</i>	Seed-borne bacterial disease	Onion			Low risk
	<i>Phakopsora pachyrhizi</i>	Asian soybean rust	Soybean			No risk
	<i>Penicillium patulum</i> + patulin toxin	Blue mould rot	Apple			Low risk (mycotoxins may survive)
	<i>Aspergillus flavus</i> + aflatoxin, thremorgenic toxin	Aspergillus ear rot	Maize, soybean, peanut			Low risk (mycotoxins may survive)
	<i>Pleospora papaveracea</i>	Root disease	Poppy			Low risk
	<i>Gibberella zeae</i> (<i>Fusarium graminearum</i>) + deoxynivalenol and zearalenone toxins	Corn stalk rot, Head scab of wheat	Maize, wheat	Seigner et al (2010) found elimination of the fungus after 2 days at 38°C		Low-medium risk (mycotoxins may survive)
	<i>Aspergillus ochraceus</i> + ochratoxine A		Maize, wheat, barley			Low risk (mycotoxins may survive)
	<i>Penicillium verrucosum</i> + ochratoxine A		Maize, wheat, barley			Low risk (mycotoxins may survive)
	<i>Fusarium sp.</i> + trichothécènes, etc.	Cereal foot rot	Wheat			Low risk
	<i>Fusarium oxysporum</i> f.sp. <i>albedinis</i>	Bayoudh	Date			No risk
	<i>Tilletia indica</i>	Karnal bunt	Wheat			High risk
	<i>Tilletia tritici</i>	Complete bunt	Wheat			Medium risk
	<i>Tilletia laevis</i>	Common bunt	Wheat			Low risk
	<i>Tilletia controversa</i>	Dwarf bunt	Wheat			Low-medium risk
	<i>Ustilago nuda</i>	Barley loose smut	Wheat, barley			Low-medium risk
	<i>Fusarium moniliforme</i> / <i>verticillioides</i> + fumonisin toxin	Fusarium ear and stalk rot	Maize			Low-medium risk
Agaricomycetes	<i>Rhizoctonia solani</i>			Seigner <i>et al.</i> , (2010) reported survival at 0.3 days at 38°C	Survives up to 20 days in MAD	

					with or without pre-pasteurisation – on the basis of RNA PCR test	
Oomycetes	<i>Phytophthora infestans</i>	Potato late blight	Potato		Survives 1 day in MAD and 1 hour in TAD	
	<i>Phytophthora ramorum</i>	Sudden oak death	Oak			Low risk
	<i>Phytophthora kernoviae</i>		Beech, rhododendron, bilberry, etc			Low risk
	<i>Phytophthora lateralis</i>		Cypress, etc			Low risk
	<i>Verticillium dahliae</i> and subsp.		Potato, OSR	Seigner <i>et al.</i> , (2010) reported survival up to 28 days at 38°C and 8 days at 55°C		Medium risk
	<i>Phytophthora pseudosyringae</i>		Bilberry, various tree spp., etc			Low risk
	<i>Aphanomyces euteiches</i>		Pea			Low-medium risk
	<i>Phytophthora cinnamomi</i>				Survives 1 day in MAD and 1 hour in TAD	
	<i>Phytophthora nicotianae</i>				Survives 1 day in MAD and 1 hour in TAD	
Chytridiomycetes	<i>Synchytrium endobioticum</i>	Potato wart	Potato	Seigner <i>et al</i> (2010) reported very long survival times in the batch process: even after 137 days' incubation (the end of the trial) in fermentation substrate at 38°C, 99% of the resting sori were intact		Low-medium risk
Phytopmyxae	<i>Spongospora subterranea</i>				Survives 3 days in MAD with	

					pre-pasteurisation; 12 days in MAD without pre-pasteurisation	
Plasmodiophoromycetes	<i>Plasmodiophora brassicae</i>			In four studies on AD, eradication, based on the results of bioassay test plants, was achieved after 21 days at 40°C or after 10 hours at 52°C, whereas the results of Engeli <i>et al</i> (1993) indicate that the pathogen can survive in AD for 14 days at 55°C	Survives 1 day in MAD and 1 hour in TAD	
Viruses	Lettuce big vein virus		Lettuce			Low risk
	Plum pox potyvirus	Sharka	Plum, peach			Low risk
	Tomato yellow leaf curl virus (TYLCV) / <i>Bemisia tabaci</i>		Tomato			Low risk
	Pepino mosaic potexvirus		Tomato			Medium-high risk
	Tomato spotted wilt virus (TSWV) / <i>Frankliniella occidentalis</i>		Tomato, tobacco			Low risk
	Tomato Mosaic Virus		Tomato	<i>TMV</i> was inactivated after a 74-day exposure in AD at 36°C, although it survived a similar treatment or 28-day exposure in thermophilic conditions (around 55°C) in two different studies		Low-Medium risk
	Potato Virus X		Potato			Low risk
	Potato Virus Y		Potato	<i>Potato Virus Y</i> in infected potatoes did not survive a MAD process for 6 hours		
Potato mop top virus		Potato			Low risk	

	Tomato bushy stunt		Tomato, pepper			Low risk
Viroids	Potato spindle tuber viroid		Potato			Low-medium risk
	Tomato chlorotic dwarf viroid					Low-medium risk
Nematodes	<i>Globodera rostochiensis</i> and <i>G. pallida</i>		Potato	Viable PCN cysts survived anaerobic digestion in sewage sludge although populations were reduced (Turner <i>et al.</i> , 1983). Similar studies by Catroux <i>et al.</i> (1983) showed that nearly 100% of the cysts of <i>G. rostochiensis</i> and <i>G. pallida</i> were killed during anaerobic digestion of sewage		Low-medium risk
	<i>Heterodera schachtii</i>		Maize, beet, etc			Low-Medium risk
	<i>Meloidogyne</i> spp.		Potato, etc			Low-medium risk
	<i>Pratylenchus</i> spp.		Potato			Low-medium risk
Seeds	Tomato seed (<i>Lycopersicon esculentum</i>) Ailsa Craig			Ryckeboer et al. 2002 reported survival of seed for 1 day at 52°C. Engeli et al. 1993 reported survival for 14 days at 55°C and 21.5 days at 35°C	Not detected after 3-6 days in MAD Not detected after 1 day in TAD Eliminated by 1 hour at 70°C	
	Black grass seed (<i>Alopecurus myosuroides</i>)				Not detected after 3-6 days in MAD Not detected after 1 day in TAD	

					Eliminated by 1 hour at 70°C	
Human pathogens/ indicators	<i>Escherichia coli</i>				1.8 log decrease at 30 days in MAD Eliminated by 1 hour at 70°C	
	<i>Salmonella</i>				3.5 log decrease at 30 days in MAD Eliminated by 1 hour at 70°C	
	<i>Clostridium botulinum</i>			No proliferation of human pathogenic Clostridia occurs under mesophilic or thermophilic conditions assessed in lab scale reactors (Dohrmann <i>et al.</i> 2011)		
	<i>C. perfringens</i>			Their <u>survival</u> during the AD process has been extensively studied and can be described as high in mesophilic AD systems (Puchajda & Oleszkiewicz 2003; Lepeuple <i>et al.</i> 2004; Watcharasukarn <i>et al.</i> 2009). Survival in TAD is less well investigated.		

3.0 Alternative approaches for phytohygiene management

3.1 Controlling digestate phytohygiene in other EU countries

3.1.1 Germany

The German Biowaste Ordinance lays down requirements on plants processing biowaste destined for use in agriculture, silviculture and horticulture. Use within the same holding as the waste arises is excluded from these requirements.

Time/temperature requirements are laid down as either 55°C for 24 hours with a minimum retention time of 20 days or, if a lower temperature or shorter retention time are employed the process must include a pre- or post-treatment at 70°C for one hour.

Additionally each facility must undertake a direct process validation, which must be completed within 12 months of commissioning for new facilities and repeated on existing facilities where processes have changed substantially. Validation for the effectiveness of a process in reducing risks to plant health entails testing 36 samples, each sample being tested on three consecutive days.

Test organisms must be placed within the part of the process responsible for thermal inactivation, although a provision is made for circumstances where the design of the system makes this impractical, in which case the "efficacy of the process with regard to sanitisation must be demonstrated in other ways by suitable experts". Test organisms are introduced into the system inside semi-permeable membranes in non-decomposable containers.

For plant pathogens the test organisms specified in the ordinance are tobacco mosaic virus (TMV), *Plasmodiophora brassicae* (the causal agent of clubroot of brassicas) and tomato seed. Testing methods and acceptable limits for the indicator organisms are specified (Bruns, 1994; Pollman and Steiner, 1994).

The ordinance also sets out a requirement for indirect monitoring, whereby temperature measurements of the part of the system responsible for thermal inactivation are taken regularly (continuously if possible) in three representative zones. A further analysis of the final digestate is also required, and a limit for seeds or reproductive parts of plants of two per litre of substrate is specified.

3.1.2 Sweden

The Swedish Certification Rules for Digestate² do not include specific requirements for plant pathogens, but do specify parameters in accordance with EU regulations for ABP inputs (pasteurisation at 70°C for one hour and a maximum particle size of 12 mm). Instead, plants processing non-ABP material must incorporate a treatment at a minimum of 55°C for at least six hours and a hydraulic retention time of at least seven days. More stringent requirements are placed on plants that do not have adequate mixing and an even temperature distribution.

3.1.3 Proposed pan-European approach

Technical discussions in preparation for proposed End of Waste Criteria for Biowaste under the Waste Framework Directive (2008/98/EC) incorporate a suggested time/temperature regime of 55°C for 24 hours and a hydraulic retention time of 20 days for effective management of biological risks in digestate not containing ABP material (Anon 2012). The same document also proposes that requirements should not be overly restrictive such that competent authorities in member countries can authorise other treatments providing that effectiveness in reducing biological risk can be demonstrated.

² <http://www.avfallsverige.se/fileadmin/uploads/Rapporter/Biologisk/B2009b.pdf>

3.2 Ability to test for pathogens in digestate or feedstock (the 'continuous surveillance' option)

If feedstock were monitored and controlled there would be a low risk of the resulting digestate being contaminated and no further tests would be required. Feedstocks would have to be tested for specified plant pathogens before they were used in AD processes. However, such an approach has severe limitations.

While it may also be possible to test all digestate for the presence of proscribed pathogens before it is considered safe, this option would require extensive and continuous testing which could be highly costly. Tests would have to be capable of detecting the lowest inoculum levels identified as a risk to crops. Highly sensitive methods, generally DNA-based, are available for major pathogens, although an enrichment step may be required for added sensitivity and to differentiate between viable and dead cells. Appropriate statistical sampling approaches would also need to be considered.

3.3 Enhanced Enzymic Hydrolysis (EEH)

The EEH process utilises a number of reactors operated in series to approximate a plug-flow mode of mixing and thus minimise any short-circuiting of feedstock. The process consists of five or six reactors operated in series. The reactors may be operated at different temperatures and HRTs in order to carry out the dual role of hydrolysis and sanitisation. The first stage of the process is the hydrolysis stage and comprises three vessels in series, each operating at around 42°C and providing an overall retention time of approximately two days. This low retention time and associated high organic loading rate provides an environment with a pH of around 5.5, which together with the elevated temperature, provides ideal conditions for acid hydrolysis of the feedstock.

The second stage of the process involves two tanks at 55°C that are operated on a fill, hold and draw basis to ensure a minimum of five hours retention time at this temperature, thus ensuring effective pathogen destruction. The temperature increase is achieved by recirculation of the first stage digestate through steam injection units. The hydrolysed and sanitised sludge from the EEH unit is then fed to a conventional MAD digester, which can be operated at a reduced HRT of between 11 to 18 days, since the first stage of hydrolysis stage has already been undertaken (Figure 1).

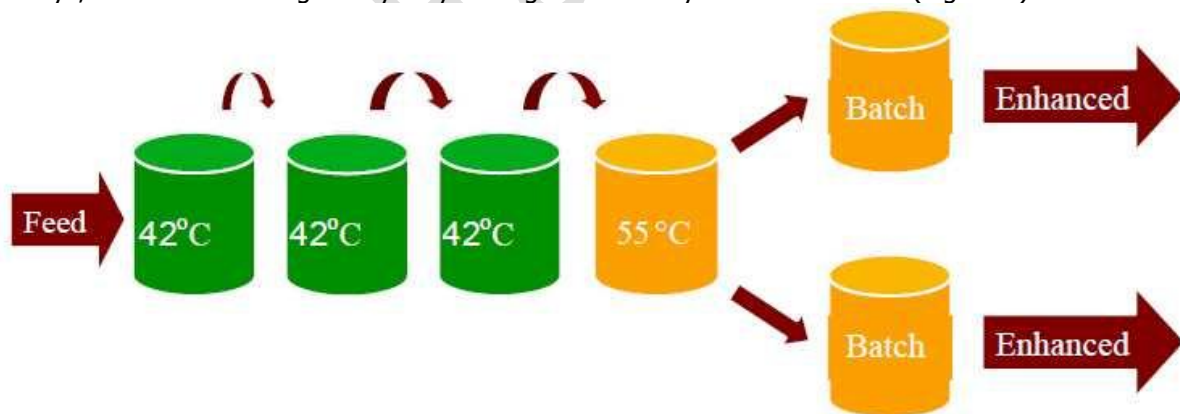


Figure 1 Typical layout of an EEH process with the reactors in green providing acid hydrolysis whereas those in yellow provide sanitisation (from Riches *et al.*, 2011)

The first full-scale EEH plant was constructed at Macclesfield in 2002 followed shortly after by plants at Bromborough and Blackburn, both treating sewage sludge and operated by United Utilities. The efficacy of the EEH unit can be seen in Figure 2 in which greater than 6-log removal of *E. coli* was observed shortly after initiation of the enhanced mode of treatment at Blackburn, providing a digestate that was completely free from *E. coli*.

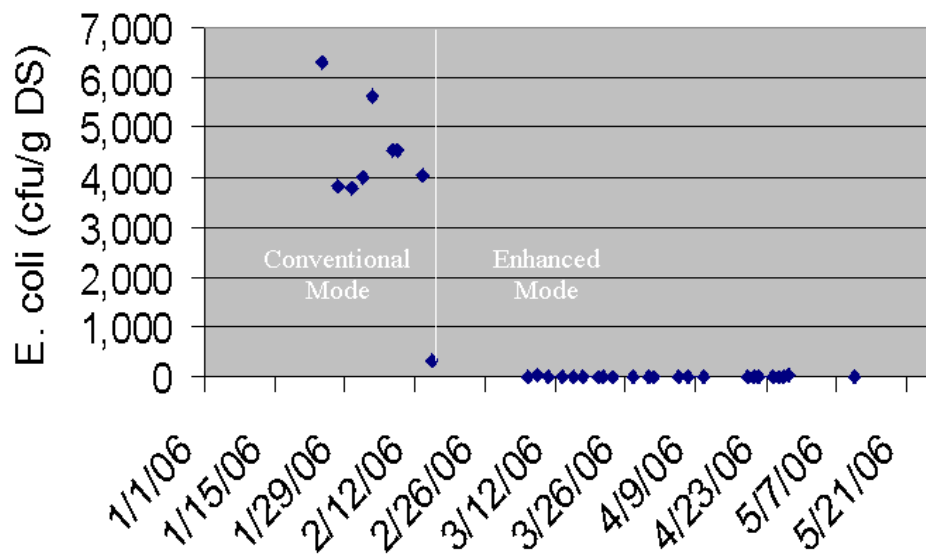


Figure 2 Rapid die-off of *E. coli* during the operation of the Blackburn EEH in enhanced mode, to provide a digestate free of this bacterium

More recently, EEH has been commissioned at King's Lynn and Great Billing (Figure 3) and operated by Anglian Water, with 6-log removal of *E. coli* reported by Riches *et al.*, (2011). At present this technology is operated predominantly using sewage sludge as a feedstock. However Wessex Water plan to treat up to 24,000 tonnes of food waste using existing wastewater digestion infrastructure, including the EEH process at their Avonmouth site near Bristol (Hills, 2011).



Figure 3 Enhanced enzymic hydrolysis reactors at the Great Billings sludge treatment centre operated by Anglian Water and achieving a 6-log removal of *E. coli*

With proper validation, EEH systems may offer a solution for microbiological hazard reduction by considering the AD process as a whole rather than reliance on a discrete pathogen kill step such as pasteurisation, however they are unlikely to achieve widespread use as capital and operating costs are typically higher than single tank systems.

3.4 The use of indicator organisms

3.4.1 Setting alternative processing parameters within the ABPR

Measures to protect against potential animal and zoonotic hazards associated with ABP material are set out in EU regulations 1069/2009EC (the control regulation) and 142/2011 EC (the implementing regulation), in which the requirement for pasteurisation at 70°C for one hour with a maximum particle size of 12 mm is specified. However, the regulation allows AD operators flexibility in employing alternative transformation methods, provided that such methods “ensure adequate reduction of biological risks”. Permitting for alternative methods is administered by AHVLA, and the UK’s approach to demonstrating pasteurisation equivalence under the ABPR provides a useful background against which to consider alternatives to pasteurisation for reduction of risks from plant pathogens.

There are several conceivable methods for demonstrating effectiveness of alternative methods to pasteurisation. At the most basic level it is possible to seed a digester with a feedstock containing indicator organisms and assay for the reduction in viable count on completion of the transformation method being tested. While this may constitute a robust validation it has several drawbacks: firstly, addition of the indicator organisms specified in 142/2011EC (*Salmonella* Senftenberg or *Enterococcus faecalis*, and parvovirus) into the feedstock itself would result in severe restrictions on that plant under a zoonosis order, and is clearly impractical. Laboratory testing of the parameters in a contained small-scale system is more practical, and indeed can be employed to test a specific time/temperature regime on indicator organisms. However this alone is not considered adequate: the approach taken by AHVLA is that each biogas plant operating pasteurisation alternatives must seek separate approval, and that any validation experiments have to be conducted on the plant itself rather than small-scale analogous systems. The rationale is to ensure that each plant *and* its operators are able to ensure adequate reduction of biological risks, and that differences in feedstock between plants do not influence the effectiveness of the site-specific transformation process. Type approval, ie permitting a specific time/temperature regime in place of pasteurisation if it has been shown to provide adequate reduction of biological risks and providing the parameters can be adequately monitored and controlled, has not been considered sufficiently robust when granting approvals for alternative transformation methods.

To validate alternative transformation approaches, an inoculum of test organism(s) is placed into the digestion or composting system within a sealed recoverable container representing the desired ‘particle size’, rather than the test organisms being added directly to the digestate feedstock. The contents of the test container are then assayed after completion of the test protocol. This approach has the advantage of testing both particle size and time/temperature within the actual facility seeking derogation from standard pasteurisation. Although relatively simple to perform in composting facilities, a validation that requires introduction of a sample capsule into an AD system may require some engineering modification such that the sample containers can be placed in appropriate locations and recovered after the required time has elapsed. Conducting tests in which indicator organisms are enclosed in semi-permeable membranes was not considered appropriate: although this would allow the effect of physicochemical conditions (for example pH, ammonia) to be assessed as well as those of time and temperature, the risk of rupture of containers or leaching of the contents was considered too great. Furthermore, whilst AD operations may well expose pathogens to a range of physicochemical conditions, these cannot be guaranteed at all times – unlike a discrete thermal process. However, semi-permeable membrane containers are recommended for use in the direct validation processes in Germany (see Section 3.1.1).

3.4.2 Possible approaches for non-ABP inputs

Spiking with known amounts of indicator organisms in recoverable containers offers an attractive solution to directly validating process efficacy. Although this would be more challenging in AD than in composting systems, operators who wish to validate alternatives to pasteurisation could consider engineering solutions which would allow such samples to be introduced to and recovered from appropriate points. Key to this approach would be selection of suitable indicator organisms to act as proxies for inactivation of pathogens. The German waste ordinance provides a precedent for this, using the highly persistent plant pathogens TMV and *Plasmodiophora brassicae* as indicators.

Various indicator organisms have been used for direct validation of composting processes, including the plant pathogens *P. brassicae*, TMV, *Fusarium oxysporum* and tomato seeds (Idelmann 2005; Noble et al 2011).

Although common in the natural environment, and likely to be present in many AD feedstocks and apparently offering the potential for indirect process validation, *E. coli* and *Salmonella* are not suitable indicators for inactivation of plant pathogens, as some of the spore-forming plant pathogens are significantly more likely to survive digestion (without pasteurisation) than these bacteria.

Other organisms which occur naturally in the AD process may also be considered suitable as indicator organisms for indirect validation. Schnürer & Schnürer (2006) present data on seven fungal species tested through a sanitisation process of 70°C for one hour. After this time, only spores of *Thermomyces lanuginosus* survived at levels above the detection limit. *Aspergillus flavus* and *fumigatus* were both inactivated, although naturally occurring *Aspergillus* species were shown to survive.

In its specification for directly validating alternatives to pasteurisation, the German Biowaste Ordinance requires the use of the highly-persistent clubroot pathogen *Plasmodiophora brassicae* as well as tobacco mosaic virus and tomato seed as indicators.

3.5 Effects of various time-temperature regimes on pathogen eradication

There have been numerous studies examining the fate of animal pathogens following exposure in organic wastes to different time-temperature regimes. These generally show a linear relationship between the logarithm of the exposure time required to inactivate the pathogen and the temperature of the waste, i.e. as the temperature decreases, the time needed to achieve inactivation increases logarithmically. For example, Aitken et al. (2006) showed that the time needed for a 10-fold (or 1- \log_{10}) reduction in the *E. coli* count in AD increased by 15 times when the temperature was reduced from 55 to 50°C. Pandey & Soupir (2011) showed a similar increase in decimal reduction time for *E. coli* when the temperature in AD was reduced from 52.5 to 37°C. Smith et al. (2004) also examined the decay kinetics of several isolates of *E. coli* and *Salmonella* spp. in nutrient broth and centrifuged sewage sludge. At 70°C, all species and serotypes were inactivated within 10 seconds of exposure. At 55°C, inactivation occurred within 20-60 minutes of exposure, with a 1 \log_{10} reduction in survivors every 3-8 minutes depending on the thermo-tolerance of the specific bacteria and the inoculation media. At 35°C, a 1.5 – 2 \log_{10} reduction in survivors occurred during a 20 day test period, but none of the test organisms were inactivated.

Feacham et al. (1983) showed that the slope of the relationship between inactivation time and temperature differed for different pathogens in sewage sludge, with a steeper slope for enteric viruses than for *Salmonella* spp. and eggs of *Ascaris* spp. Burge (1983) also showed that the effect of a 5°C decrease in the temperature of sewage on the additional time required to achieve a 1 \log_{10} reduction in enteric pathogens differed between pathogens. Reducing the temperature of the sludge from 60°C to 55°C increased the required time for achieving a 1 \log_{10} reduction in Adenovirus by 65, whereas the same temperature reduction increased the required time for *Histolytica* cysts by only 1.8. Murphy et al (2002) also showed that the effect of reducing the temperature of pathogen-inoculated meat products from 70°C to 55°C on the time needed to achieve a decimal reduction of *Salmonella* spp. was different to that for *Listeria innocua*. For *Salmonella* spp., the time increased from 0.25 to 27 minutes, but for *L. innocua*, the time increased from 0.18 to 192 minutes.

Schnürer & Schnürer (2006) also showed that the relative effectiveness of a 1-h treatment at 70°C or thermophilic anaerobic digestion at 55°C with a hydraulic retention time of 19 days in inactivating fungi in organic waste differed between species. For *Paecilomyces* species and *Trichocladium minimum*, the 1-h high temperature treatment was more effective, but for *Aspergillus* and *Cladosporium* species, the thermophilic AD treatment was more effective.

Carrington et al. (1982) demonstrated a more complex interaction between the effects of temperature and retention time in anaerobic digestion on *Salmonella* Dusseldorf populations. At 35°C, there was a constant logarithmic decay rate in the population of viable *S. Dusseldorf* with retention time, i.e. there

was a 1-log reduction in the viable population every 40 minutes. However, at 48°C, the decay rate decreased with time, so there was a 3-log reduction in the viable population in the first two hours, but less than a 1-log reduction in the subsequent 6 hours. Whitmore & Robertson (1995) also found that the rate of decay in viable oocysts of *Cryptosporidium parvum* in sewage sludge was inconsistent with different time-temperature regimes. At temperatures between 4°C and 20°C, there was a near constant decline in the percentage viability of oocysts, whereas at 37°C, the rate of decline decreased with increasing retention time.

Jones (1976) found that rate of decline of *Salmonella* spp. in cattle slurry was influenced by the size of the viable population introduced. This could influence the relationship between temperature and time to extinction, with small populations of pathogens being eradicated in shorter time periods.

There are few plant pathogens for which there are comprehensive temperature–time matrices for inactivation, enabling the equivalence of different treatments to be compared under the same conditions (Noble & Roberts, 2004; Noble et al. 2009). Data obtained in different experiments, particularly in organic wastes (which are inherently variable), may be influenced by other factors than the time and temperature of exposure. Unless very frequent sampling is conducted in experiments, shorter times than those reported for achieving inactivation of pathogens may have been adequate. This makes determination of equivalent time-temperature inactivation treatments less precise.

3.6 Difficulties with transposing time-temperature regimes for pasteurisation equivalence in AD from other treatment systems

While there is a significant volume of data on the effects on pathogens of exposure to heat in compost, soil and abiotic systems, there are few studies examining pathogen destruction following exposure to equivalent time-temperature regimes in different biological or abiotic systems. This means that inferences on the fate of pathogens under one system are not necessarily accurate for the fate of those same pathogens under different systems.

Heat appears to be the most important factor for the elimination of plant pathogens during composting (Bollen & Volker, 1996; Noble et al., 2009). Moisture content, as well as other chemical and microbial factors may also influence pathogen destruction. Toxic volatile organic compounds such as hydrogen sulphide and organic acids in AD may also have significant effects on pathogen destruction (Termorshuizen et al., 2003).

Seigner et al. (2010) showed that plant pathogen kill was improved in anaerobic digestate compared with the same time-temperature treatments in water. Inactivation of *Plasmodiophora brassicae* in AD at 52°C has been achieved within 1 day (Ryckeboer et al., 2002) and within 21 days at 40°C (Termorshuizen et al., 2003). In compost, the same organism has been found to be viable after 7 days at 65°C (Ylimaki et al., 1983; Noble et al., 2011).

Rhizoctonia solani and *Verticillium dahliae* were inactivated in less than 8 hours at 40-50°C in water and moist systems (Miller & Stoddard, 1956; Pullman et al., 1981; van Loenen et al., 2003), whereas reports for the same organisms in compost give eradication times of more than 7 days at equivalent compost temperatures (Yuen & Raabe, 1984; Bollen et al., 1989; Christensen et al., 2001; Noble et al., 2004).

Appendix 1 tabulates numerous data on the time required at different temperatures for inactivation of a range of plant pathogens in anaerobic digestion, composting and incubation studies. As expected, this shows viral plant pathogens to have the most tolerance to heat, whereas bacterial plant pathogens are generally more sensitive to heat than fungi. As with animal pathogens, there is a logarithmic relationship between the time to inactivation and the exposure temperature for plant pathogens. However, the effect of temperature on the inactivation time differs between plant pathogens and between different systems. For *Phytophthora nicotianae* and *Verticillium albo-atrum* (incubator studies) the inactivation time at 55°C was less than 1% of that at 40°C. For *Verticillium albo-atrum*, *V. dahliae* (anaerobic digester), *Fusarium oxysporum* (composting) and *Thielaviopsis basicola* (incubator), the inactivation time at 55°C was more than 7% of that at 40°C.

3.7 The food industry approach to pasteurisation

Pasteurisation is the term given to a process used in the food industry whereby a foodstuff is heated to a temperature sufficient to significantly reduce microbial load while maintaining organoleptic qualities. The heat treatment is applied for a precise length of time and the foodstuff is then cooled immediately. There are several forms of pasteurisation, of which the principal ones are high temperature short time (HTST) and low temperature long time (LTLT). The temperature / time combinations within each form can vary with the type of foodstuff treated.

A common misconception is that pasteurisation is equivalent to sterilisation, in other words that it completely eliminates microorganisms, while in fact it actually only reduces the microbial load by several logs; for instance pasteurised milk still contains a viable natural microflora, and will spoil if not kept refrigerated. However the 5-log reduction which the pasteurisation process can mediate is expected to reduce the numbers of any contaminating pathogens to a level in which they do not pose a hazard (Pearce et al., 2012). Spores, e.g. of *Bacillus cereus*, are not affected by any form of pasteurisation (Griffiths, 1992).

Pasteurisation regimes in the food industry encompass a wide range of time and temperature options and it is difficult to compare their effect on microbiological hazards without resort to experimental validation.

3.7.1 Pasteurising milk

Several species of microbial pathogens are considered to have the potential to contaminate and be transmitted by milk or dairy products (Hudson et al., 2003), including *Bacillus* spp., *Brucella*, *Cryptosporidium*, *Campylobacter* spp., *Clostridium botulinum*, *Coxiella burnetii*, *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Mycobacterium avium* subsp. *paratuberculosis* (MAP), *Mycobacterium bovis*, streptococci, *Salmonella*, *Staphylococcus aureus*, and *Yersinia enterocolitica*.

Pasteurisation of milk has been employed by the dairy industry for over a century, originally to kill the bacterial agent of tuberculosis, but with conditions changed subsequently to be able to mediate a 5-log reduction in viable *Coxiella burnetii*, the agent of Q-fever and the most heat-resistant non-sporulating pathogen which might contaminate milk (Holsinger et al., 1997). The theory is that if this bacterium is thus affected then the viability of other pathogenic types should be reduced to a similar or greater extent.

Currently in the UK, industrial practice conforms to European regulatory requirements. European Commission Regulation 2074/2005 states:

"When raw milk or dairy products undergo heat treatment, food business operators must ensure that this satisfies the requirements laid down in Chapter XI of Annex II to Regulation (EC) No 853/2004. In particular, they shall ensure, when using the following processes, that they comply with the specifications mentioned:

(a) Pasteurisation is achieved by a treatment involving:

(i) a high temperature for a short time (at least 72 °C for 15 seconds);

(ii) a low temperature for a long time (at least 63 °C for 30 minutes); or

(iii) any other combination of time-temperature conditions to obtain an equivalent effect, such that the products show, where applicable, a negative reaction to an alkaline phosphatase test immediately after such treatment."

Alkaline phosphatase is an enzyme naturally present in all raw milks, which is used as an indicator of correct milk pasteurisation. It has a thermal resistance greater than that of *Coxiella burnetii*, and therefore if it is inactivated by the pasteurisation process then the process is considered to have been effective in reducing the microbial load (Murthy et al., 1993).

3.7.2 Pasteurising egg

Egg products can also be subject to pasteurisation in the food industry. The Egg Regulations (Anonymous, 1993) state that liquid egg must be pasteurised prior to retail sale:

"Whole egg and yolk shall be pasteurised by being-

*(a) retained at a temperature of not less than 64.4°C for at least 2 minutes and 30 seconds, or
(b) retained at another temperature and for another period of time to achieve at least the same degree of destruction of vegetative pathogenic organisms as if treated by the process specified in paragraph (a) above, and then as quickly as possible cooled to a temperature below 4°C and retained at that temperature unless otherwise preserved, save that the temperature of whole egg or yolk may be held above 4°C solely for the purpose of dissolving added sugar or salt after which the whole egg or yolk shall be immediately cooled to below 4°C."*

The Regulations also state that an enzyme inactivation test (α -amylase test) shall be carried out as a means of assessing whether liquid egg has been pasteurised. The rationale which underlies this approach is that if the heat treatment is sufficient to denature the enzyme then it will also be sufficient to ensure that no bacterial pathogens, in particular *Salmonella* (the pathogenic species of major concern as regards contamination and transmission by eggs (Cogan and Humphrey, 2003)), survive. Alpha-amylase is a naturally occurring enzyme found in egg (Murthy, 1970). Heat inactivation of this enzyme has been found to parallel that observed for *Salmonella* Senftenberg, the most heat resistant of the salmonellas.

Other foodstuffs which are industrially pasteurised include fruit juices, and alcoholic beverages such as beer and wine. Generally, this is performed to eliminate spoilage organisms such as yeasts and moulds. There do not appear to be regulations or common industry standards for pasteurisation of these products.

3.7.3 Pasteurisation Units

The concept of Pasteurisation Units (PU) sets out to quantify the amount of pasteurisation that has taken place by expressing the process in terms of time, temperature and a Z-value which varies depending on the heat stability of the organism(s) in question. One PU is defined as the sterilising effect seen when a substrate is held at a base temperature for one minute. A minimum temperature is defined below which no contribution is made to PU and the effect on increasing temperature above the base is determined by the Z value, defined as the temperature change required to reduce the survival of target organism(s) by 10-fold (Del Vecchio et al., 1951).

Since a time-temperature regime for pasteurisation currently exists in the PAS110 specification, it is conceivable that the PU approach could be useful in determining acceptable alternative time/temperature combinations. However, the Z value is dependent on the persistence of the microbial hazard (and conceivably on the chemical environment during pasteurisation) so some validation would be required to ensure that an alternative regime proposed was equivalent to the PAS110 pasteurisation treatment as currently defined.

3.8 Energy implications of different time/temperature approaches

Ziemba and Peccia (2011) examined the net energy production associated with pathogen inactivation in sewage sludge for a range of thermal options that included: MAD, TAnD at 50 and 55°C (all with a 15 day retention time), temperature phased anaerobic digestion at 50 and 55°C and a retention time of 5 days followed by MAD for 15 days, and batch pasteurisation of 5 hours at 60°C and 1 hour at 70°C both followed by MAD for 15 days. They found that at temperatures of 60°C or above there was a sharp increase in the inactivation rate coefficient of *E. coli* and that this was associated with permanent ribosome damage. At 55°C or below, although inactivation rates were high there was no associated change in the structure of the cell to indicate effective and permanent inactivation. Perhaps most surprisingly, they observed that net energy production was similar for all reactor configurations and thus concluded that energy consumption is not a significant barrier to improving the pathogen quality of biosolids.

4.0 An alternative phytohygiene control approach for the UK?

4.1 Introduction

In considering an alternative to pasteurisation we have examined the following:

- Exemption of certain feedstocks where risk assessment indicates this is warranted or where the feedstocks have already undergone a similar procedure to the pasteurisation step;
- Use of alternative time/temperature regimes;
- Restriction of particularly high risk feedstocks (such as quarantine plant wastes) to defined 'special measures' or licensed facilities;
- Use of indicator organisms for process-specific validation.

4.2 Exemption of specific feedstocks from a pasteurisation requirement

There are certain circumstances where specific non-ABP feedstocks could be exempted from the pasteurisation requirement. This could mean that, in the PAS, if all non-ABP feedstocks arose from food or drinks manufacturing they must have been treated through a thermal process that gives equivalent PU to 70°C for one hour.

Although MAD without a discreet pasteurisation step cannot be guaranteed to eliminate plant pathogens of interest, the current PAS110 exemption from pasteurisation where inputs arise from, are digested on and returned to the same holding could remain in place, so long as users of this exemption are made aware of the potential phytohygienic risks associated with this approach.

Where there is any doubt, operators could implement the new validation approach (Section 4.5).

4.3 Use of alternative time/temperature regimes

The use of alternative temperature and time regimes has been suggested, for example see Table 4-1. In principle these could be acceptable but would require validation as suggested in Section 4.5.

Table 4-1 Combinations of temperatures and Minimum Guaranteed Retention Times (MGRTs) for sanitation, equivalent to 70°C for 1 hour – example from Denmark (Bendixen, 1994 & 1999; Bendixen & Bennetzen 1995)

Thermophilic temperature (°C)	MGRT at thermophilic temperature ^a (hours)	MGRT by treatment in a separate pasteurisation tank ^b (hours)	
		before thermophilic digestion ^c	before mesophilic digestion ^d
52.0	10		
53.5	8		
55.0	6	5.5	7.5
60.0		2.5	3.5

- a) The hydraulic retention time (HRT) in the digester must be at least 7 days
- b) Digestion may take place either before or after pasteurisation
- c) See point a)
- d) The mesophilic digestion temperature must be between 20°C and 52°C. The hydraulic retention time must be at least 14 days.

4.4 Restriction of high risk feedstocks

High risk feedstocks would include material known to contain pathogens for which there is zero tolerance (such as quarantine plant pathogens that are under statutory control), for example the potato ring rot and brown rot pathogens, *Clavibacter michiganensis* subsp. *sepedonicus* and *Ralstonia solanacearum*. Quarantine pathogens are highly unlikely to be present in material destined for AD except in crop waste arising from an interception of infected plant material or outbreak of quarantine diseases. In such cases it is conceivable that AD may be used as a route for safe disposal of infected plant material.

If a statutory body recommended treatment of high risk feedstocks containing plant quarantine organisms under statutory control through AD, then it would be essential that any process intended to achieve pathogen kill was completed as a batch process that could not be bypassed, and that it had been validated for the particular microbial hazards in question. The most effective way to ensure this would be to incorporate a pasteurisation step.

4.5 Process-specific validation

In recommending alternatives to pasteurisation it is important to establish equivalence to pasteurisation in terms of ability to reduce pathogen risk to an acceptable level. Since all digesters differ in operating parameters (for example temperature, retention time, vessel design) and, crucially, feedstock, we are not recommending a defined set of digestion parameters to obtain equivalence to pasteurisation since these may not be equally effective across all digester types. Instead we propose a validation process by which operators can demonstrate that their process, operated by their personnel, is sufficiently effective at reducing pathogen risk. This approach has the advantage of being in harmony with the approach taken in implementing ABP requirements.

For validation we propose that any suggested alternative to pasteurisation be tested for its ability to achieve a defined level of kill of indicator organisms introduced into the digester. To aid analysis we propose that these organisms are introduced in sealed containers for ease of recovery and subsequent analysis, and because inoculating an entire reactor with a detectable level of indicator organism would not be practicable. We suggest that more persistent organisms for which viability assays can be conducted are chosen as indicators, and for this reason propose *Plasmodiophora brassicae* and tomato seed.

Our suggested indicators differ slightly from other process validation approaches, for example the German Biowaste Ordinance (Anon, 2006b) which specifies *Plasmodiophora*, tomato seed and tobacco mosaic virus (TMV) as indicators. We do not propose TMV since we consider this too persistent to be a workable indicator but suggest the adoption of *Plasmodiophora*.

4.5.1 Validation protocol

Direct validation requires AD processes to accommodate introduction and subsequent recovery of a capsule containing the indicator organisms *Plasmodiophora brassicae* (at a minimum of 3 g gall tissue/capsule) and tomato seed (cultivar Ailsa Craig, a minimum of 15 seeds/capsule). The capsule must be of sufficient size to contain the required titre of indicators while allowing sufficient thermal conductance to ensure that the centre of the capsule reaches the required temperature during the specified duration of the sanitisation step. The precise dimensions and construction of the capsule may need to be determined experimentally for each validation.

Sufficient test capsules must be used to ensure that validation is achieved throughout the process in which the treatment is taking place, but we recommend a minimum of three capsules.

Capsules must be in place within the process for the period of time specified by the treatment under investigation. On removal, capsules must be subjected to tests as described below, commencing within 24 h of removal from the facility.

The process will be considered to have passed if viable tomato seed are undetectable and if *P. brassicae* bait plant tests do not result in infection as determined by real-time PCR assays (see below).

Testing methods

Tests for indicator organisms must be capable of ascertaining the viability of organisms. For *P. brassicae* this must involve incubation with bait plants prior to detection. Viability of the *P. brassicae* test material must be ascertained either before the test is carried out or by inclusion of appropriate control material (ie material not subjected to the treatment under validation) in testing. Proposed assay methods for *P. brassicae* are based on the methodology set out in the German Biowaste Ordinance (Anon, 2006b) with the addition of a real-time PCR assay to identify infected bait plants (Noble *et al.*, 2011).

For tomato, viability must be determined by germination or by methods described by Anon (2006) and Pollmann and Steiner (1994). The germinating capacity of the batch of tomato seed used in tests must be measured before tests commence and must be at least 90%.

Consultation copy

5.0 References

Adams PB (1987) Effects of soil temperature, moisture and depth on survival and activity of *Sclerotinia minor*, *Sclerotium cepivorum*, and *Sporidesmium sclerotivorum*. *Plant Disease* **71**: 170-174

ADAS/AEA (2011) Implementation of AD in England & Wales: Balancing optimal outputs with minimal environmental impacts - Impact of using purpose grown crops. Defra funded project FFG 1001 / Contract Reference AC0409
<http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17396#Description>)

AHVLA (2012) Manure <http://animalhealth.defra.gov.uk/managing-disease/animalbyproducts/compost-biogas-manure/manure.htm>

Aitken MD, Sobsey MD, Van Abel NA, Blauth KE, Singleton DR, Crunk PL, Nichols C, Walters GW & Schneider M (2007) Inactivation of *Escherichia coli* O157:H7 during thermophilic anaerobic digestion of manure from dairy cattle. *Water Research* **4**:1659-1666.

Anon (1993) The Egg Products Regulations. SI 1520. HMSO, London

Anon (2006) International rules for seed testing. The International Seed Testing Association, Bassersdorf, Switzerland

Anon (2006b) Ordinance on the Utilisation of Biowastes on Land used for Agricultural, Silvicultural and Horticultural Purposes (Ordinance on Biowastes - BioAbfV). <http://www.bmu.de/en/topics/water-waste-soil/waste-management/acts-and-ordinances/acts-and-ordinances-in-germany/>

Anon (2012) Technical report for end of waste criteria on biodegradable waste subject to biological treatment. Third working document, August 2012. JRC/IPTS
http://susproc.jrc.ec.europa.eu/activities/waste/documents/IPTS_EoW_Biodegradable_waste_3rd_working_document_wo_line_nr.pdf

Avgelis AD & Manios VI (1992) Elimination of cucumber green mottle mosaic tobamovirus by composting infected cucumber residues. *Acta Horticulturae* **302**: 311-314

Bega RV & Smith RS (1962) Time-temperature relationships in thermal inactivation of sclerotia of *Macrophomina phaseoli*. *Phytopathology* **52**: 632-635

Bendixen HJ (1994) Safeguards against pathogens in Danish biogas plants. *Water Science and Technology* **2**[13]: 171-180

Bendixen, HJ & Bennetzen O (1995) Smitstofreduktion i biomasse. Landbrug og Fiskeriministeriet, Veterinærdirektoratet

Bendixen HJ (1999) Hygienic safety – results of scientific investigations in Denmark. In: IEA Bioenergy workshop: Hygienic and environmental aspects of anaerobic digestion: Legislation and experiences in Europe. Conference proceedings ISBN 3-930511-65-7

Bollen GJ & Volker D (1996) Phylogenetic aspects of composting. In: de Bertoldi M, Sequi P, Lemmes B, Papi T, eds. *The Science of Composting*. Glasgow, UK: Blackie Academic & Professional, 233-246

Bollen GJ, Volker D & Wijnen AP (1989) Inactivation of soil-borne plant pathogens during small-scale composting of crops residues. *Netherlands Journal of Plant Pathology* **95**: 19-30

Broadbent L (1965) The epidemiology of tomato mosaic XI. Seed transmission of TMV. *Annals of Applied Biology* **56**:177-205

BSI (2010) PAS110:2010 Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials. British Standards Institution, London

Burge WD (1983) Monitoring pathogen destruction. *BioCycle* March/April: 48-50

Carrington EG, Harman SA & Pike EB (1982) Inactivation of *Salmonella* during anaerobic digestion. *Journal of Applied Bacteriology* **53**: 331-333

Catroux G, L'Hermite P & Suess E (1983) Influence of sewage sludge application on physical and biological properties of soils. (Papers presented at the seminar on the influence of sewage sludge application on physical and biological properties of soils, Munich, GFR, June 23-24). D. Reidel Publishing Company, Dordrecht, The Netherlands. pp. 243-249

Christensen KK, Kron E & Carlsbaek M (2001) *Development of a Nordic System for Evaluating the Sanitary Quality of Compost*. Copenhagen: Nordic Council of Ministers

Cogan, TA & Humphrey, TJ (2003) The rise and fall of *Salmonella* Enteritidis in the UK. *Journal of Applied Microbiology* **94**: 114S-119S

Coventry E, Noble R, Mead A & Whipps JM (2002) Control of Allium white rot (*Sclerotium cepivorum*) with composted onion waste, *Soil Biology and Biochemistry* **34**[7]: 1037-1045

Date H, Nasu H & Hatamoto M (1993) Thermal death range of *Pseudomonas solanacearum* under various conditions. *Annals of the Phytopathological Society of Japan* **59**: 709-713

Del Vecchio HW, Dayharsh CA & Baselt FC (1951) Thermal death time studies on beer spoilage organisms. *American Society of Brewing Chemists Proceedings* **50**: 45-50

Dohrmann A, Baumert S, Klingebiel L, Weiland P & Tebbe C (2011) Bacterial community structure in experimental methanogenic bioreactors and search for pathogenic clostridia as community members. *Applied Microbiology and Biotechnology* **89**: 1991-2004

Elorrieta MA, Suarez-Estrella F, Lopez MJ, Vargas-Garcia MC & Moreno J (2003) Survival of phytopathogenic bacteria during waste composting. *Agriculture Ecosystems & Environment* **96**: 141-146

Engeli H, Eidelmann W, Fuchs J & Rottermann J (1993) Survival of plant pathogens and weed seeds during anaerobic digestion. *Water Science and Technology* **27**[2]: 69-76

Fayolle L, Noble R, Coventry E, Aime S & Alabouvette C (2006) Eradication of *Plasmodiophora brassicae* during composting of wastes. *Plant Pathology* **55**: 553-558

Feacham RG, Bradley DJ, Garelick H & Mara DD (1983) Survival of pathogenic microorganisms and parasites in excreta, manure and sewage sludge. *Revue Scientifique Technique Office International Epizooties* **10**: 813-846

Gallo L, Siverio F & Rodriguez-Perez AM (2007) Thermal sensitivity of *Phytophthora cinnamomi* and long-term effectiveness of soil solarisation to control avocado root rot. *Annals of Applied Biology* **150**: 65-73

Griffiths, MW (1992) *Bacillus cereus* in liquid milk and other milk products. *Bulletin of the International Dairy Federation* **275**: 36-39

Grushevoi SE & Levykh PM (1940) Possibility of obtaining seed-bed free of infection in compost heaps. *Vseritniy Nauchnyi Issedovateljskiy Instytyt Tabachno Makhorochnyk Prodyktiv, USSR* **141**: 42-48

Herrmann I, Meissner S, Baechle E, Rupp E, Menke G, & Grossmann F (1994) Impact of the rotting process of biodegradable material of household garbage on the survival of phytopathogenic organisms and of tomato seeds. *Zeitschrift fuer Pflanzenkrankheiten und Pflanzenschutz*, **101**

- Hoitink HAJ, Herr LJ & Schmitthenner AF (1976) Survival of some plant pathogens [*Phytophthora cinnamomi*, *Pythium irregulare*, *Rhizoctonia solani*, *Botrytis cinerea*, *Erwinia carotovora chrysanthemi*] during composting of hardwood tree bark *Phytopathology* **66**[11]: 1369-1372
- Holsinger VH, Rajkowski KT & Stabel JR (1997) Milk pasteurisation and safety: a brief history and update. *Scientific and Technical Review of the Office of International Epizootology* **16**: 441-451
- Hudson A, Wong T & Lake R (2003) Pasteurisation of dairy products: times, temperatures and evidence for control of pathogens. Report for the New Zealand Food Safety Authority. http://foodsafety.govt.nz/elibrary/industry/Pasteurisation_Dairy-Science_Research.pdf
- Idelmann M (2005) Hygienisierung von Kompost: Möglichkeiten zum Nachweis einer erfolgreichen Abtötung von Pathogenen und Unkrautsamen. PhD thesis, University of Kassel, Germany
- Jones PW (1976) The effect of temperature, solids content and pH on the survival of salmonellas in cattle slurry. *British Veterinary Journal* **132**: 284-293
- Kaemmerer D (2009) Quantification of viable cells of *Clavibacter michiganensis* subsp. *sepedonicus* in digester material after heat treatment by TaqMan®BIO-PCR. *Journal of Plant Diseases and Protection* **116**: 10-16
- Lepeuple AS, Gaval G, Jovic M & de Roubinet MR (2004) Literature review on levels of pathogens and abatements of them in the field of sludge, soil and treated biowaste. European Commission project 2004 — Horizontal — HYG (SSPI-CT-2004- 513660)
- McGovern RJ, McSorley R & Urs RR (2000) Reduction of *Phytophthora* blight of Madagascar periwinkle in Florida by soil solarisation in autumn. *Plant Disease* **84**: 185-191
- McLean KL, Swaminathan J & Stewart A (2001) Increasing soil temperature to reduce sclerotial viability of *Sclerotium cepivorum* in New Zealand soils. *Soil Biology & Biochemistry* **33**: 137-143
- Mihail JD & Alcorn SM (1984) Effects of soil solarization on *Macrophomina phaseolina* and *Sclerotium rolfsii* *Plant disease* **68**[2]: 156-159
- Miller PM & Stoddard EM (1956) Hot-water treatment of fungi infecting strawberry roots. *Phytopathology* **46**: 694-696
- Murphy RY, Duncan LK, Johnson ER, Davis MD & Smith JN (2002) Thermal inactivation D- and z-Values of *Salmonella* Serotypes and *Listeria innocua* in chicken patties, chicken tenders, franks, beef patties, and blended beef and turkey patties. *Journal of Food Protection* **65**:53–60
- Murthy GK (1970) Thermal inactivation of alpha-amylase in liquid egg products. *Journal of Food Science* **35**: 352-356
- Murthy GK, Kleyn D, Richardson T & Rocco RM (1993) Alkaline phosphatase methods. In: *Standard methods for the examination of dairy products*, 16th Ed. (R.T. Marshall, ed.). American Public Health Association, Washington, DC, pp413-431
- Noble R & Roberts SJ (2004) Eradication of plant pathogens and nematodes during composting: a review. *Plant Pathology* **53**: 548-568
- Noble R, Jones PH, Coventry E, Roberts SJ, Martin M & Alabouvette C (2004) To support the development of standards for compost by investigating the effect of the composting process on particular plant, animal and human pathogens known to be of concern to high quality end-uses. Report STA0012. The Waste and Resources Action Programme, Banbury, Oxfordshire, UK
- Noble R, Elphinstone JG, Sansford CE, Budge GE & Henry CM (2009) Management of plant health risks associated with processing of plant-based wastes: a review. *Bioresource Technology* **100**: 3431-3446

- Noble R, Dobrovin-Pennington A, Pietravalle S, Weekes R & Henry CM (2011) Indicator organisms for assessing sanitization during composting of plant wastes. *Waste Management* **31**: 1711–1719
- Pandey PK, Soupir ML (2011) *Escherichia coli* inactivation kinetics in anaerobic digestion of dairy manure under moderate, mesophilic and thermophilic temperatures. *AMB Express* **1**: 18
- Pearce LE, Smythe BW, Crawford RA, Oakley E, Hathaway SC & Shepherd JM (2012) Pasteurization of milk: the heat inactivation kinetics of milk-borne dairy pathogens under commercial-type conditions of turbulent flow. *Journal of Dairy Science* **95**: 20-35
- Pollmann BR & Steiner AM (1994) A standardized method for testing the decay of plant diaspores in biowaste composts by using tomato seed. *Agribiological Research* **47**[1]: 24-31
- Puchajda B & Oleszkiewicz J (2003) Single and Two-stage anaerobic digestion: Hydrolysis, acidification and pathogen inactivation. Proceedings of the Water Environment Federation. WEFTEC Los Angeles, CA. Session 61, pp. 284-301
- Pullman GS, DeVay JE & Garber RH (1981) Soil solarization and thermal death: a logarithmic relationship between time and temperature for four soil-borne plant pathogens. *Phytopathology* **71**: 959-964
- Riches S, Oliver B, Brown C & Allen J (2011) Delivery and performance of the Great Billing Advanced digestion plant as part of Anglian Water's AMP4 biosolids sub-programme. In: *16th European Biosolids and Organic Resources Conference*. Ed. Horan, N.J. Aqua Enviro, Wakefield
- Robinson K & Foster G (1987) Control of potato blackleg by tuber pasteurisation: the determination of time-temperature combinations for the inactivation of pectolytic erwinia. *Potato Research* **30**: 121-125
- Ryckeboer J, Cops S & Coosemans J (2002) The fate of plant pathogens and seeds during anaerobic digestion and aerobic composting of source separated household wastes. *Compost Science & Utilization* **10**[3]: 204-216
- Schnürer A & Schnürer J (2006) Fungal survival during anaerobic digestion of organic household waste. *Waste Management* **26**: 1205-1211
- Seigner L, Friedrich R, Kaemmerer D, Büttner P, Poschenrieder G, Hermann A & Gronauer A (2010) Hygienisierungspotenzial des Biogasprozesses. Bayerische Landesanstalt für Landwirtschaft (LfL). Freising-Weihenstephan, Germany
- Smith SR, Lang NL, Gao L & Spanoudaki K (2004) Factors controlling pathogen destruction during anaerobic digestion of biowastes. In: *Biodegradable and residual waste management, Proceedings of CalRecovery-Europe Ltd Conference, Harrogate*, pp. 238-247
- Suarez-Estrella F, Vargas-Garcia MC, Elorrieta MA, Lopez MJ & Moreno J (2003) Temperature effect on *Fusarium oxysporum* f.sp. *melonis* survival during horticultural waste composting. *Journal of Applied Microbiology* **94**: 475-482
- Talboys PW (1961) Time-temperature requirements for killing *Verticillium albo-atrum* in hop waste. *Plant Pathology* **10**: 162-163
- Termorshuizen AJ, Volker D, Blok WJ, ten Brummeler E, Hartog BJ, Janse JD, Knol W & Wenneker M (2003) Survival of human and plant pathogens during anaerobic mesophilic digestion of vegetable, fruit and garden waste. *European Journal of Soil Biology* **39**: 165-171
- Turner J, Stafford DA & Hughes DE (1983) The reduction of three plant pathogens (*Fusarium*, *Corynebacterium* and *Globodera*) in anaerobic digesters. *Agricultural Wastes* **6**: 1-11

van Loenen CA, Turbett Y, Mullins CE, Feilden NEH, Wilson MJ, Leifert C & Seel WE (2003) Low temperature short duration steaming of soil kills soil-borne pathogens, nematode pests and weeds. *European Journal of Plant Pathology* **109**: 993-1002

Watcharasukarn M, Kaparaju P, Steyer JP, Krogfelt KA & Angelidakiet I (2009) Screening *Escherichia coli*, *Enterococcus faecalis*, and *Clostridium perfringens* as Indicator Organisms in Evaluating Pathogen-Reducing Capacity in Biogas Plants. *Microbial Ecology* **58**: 221–230

Whitmore TN & Robertson LJ (1995) The effect of sewage sludge treatment processes on oocysts of *Cryptosporidium parvum*. *Journal of Applied Bacteriology* **78**: 34-38

Ylimaki A, Toivianen A, Kallio H & Tikanmaki E (1983) Survival of some plant pathogens during industrial scale composting. *Annales Agriculturae Fenniae* **22**: 77-85

Yuen GY & Raabe RD (1984) Effects of small-scale aerobic composting on survival of some fungal plant pathogens. *Plant Disease* **68**: 134–6

Consultation copy

Appendix 1

Time-temperature treatments that resulted in plant pathogen inactivation in the same experiments

SYSTEM/ Pathogen type	Inoculum	Feed- stocks	Detection method	Hours to extinction at (°C):											Reference
				35	40	45	50	55	60	65	70	75	80	85	
ANAEROBIC DIGESTION/ Fungi															
<i>Verticillium albo-atrum</i>	mycelium	silage	plating PCR	-	672	-	-	192	-	-	-	-	-	-	Seigner et al. 2010
<i>Verticillium dahliae</i>	hops	silage	plating PCR	-	672	-	-	192	-	-	-	-	-	-	Seigner et al. 2010
COMPOST/ Fungi															
<i>Fusarium oxysporum</i>				-	-	-	-	-	-	-	-	-	-	-	
f.sp. <i>cepae</i>	chlamydo- spores	green wastes	plating	-	-	168	24	-	-	-	-	-	-	-	Noble et al. 2011
f.sp. <i>radicis-lycopersici</i>	chlamydo- spores	green wastes	plating	-	336	168	96	24	-	-	-	-	-	-	Noble et al. 2011
<i>Rhizoctonia solani</i>	mycelium	green waste	plating	-	168	-	24	-	-	-	-	-	-	-	Noble et al. 2004
<i>Sclerotium cepivorum</i>	sclerotia	onion waste	plating	-	-	168	72	-	-	-	-	-	-	-	Coventry et al. 2002
COMPOST/ Oomycetes															
<i>Phytophthora cinnamomi</i>	mycelium	green wastes	plating	-	72	24	-	-	-	-	-	-	-	-	Noble et al. 2011
<i>Phytophthora ramorum</i>	mycelium	green wastes	plating	240	24	-	-	-	-	-	-	-	-	-	Noble et al. 2011
COMPOST/ Plasmodiophoromycetes															
<i>Plasmodiophora brassicae</i>	galls	green wastes	bioassay	-	-	-	168	-	24	-	-	-	-	-	Fayolle et al. 2006

COMPOST/ Viruses															
<i>Tobacco Mosaic Virus</i>	tobacco leaves	tobacco	bioassay	-	-	-	-	-	192	-	120	-	-	-	Ryckeboer et al. 2002
INCUBATOR or WATER BATH/ Bacteria															
<i>Pectobacterium carotovorum</i>	suspension	pepper wastes	plating	-	-	-	15	-	1	-	0.5	-	-	-	Elorrieta et al. 2003
<i>Pectobacterium carotovorum</i> pv. <i>atroseptica</i>	suspension		plating	-	1.33	-	0.3	-	-	-	-	-	-	-	Robinson & Foster 1987
<i>Pseudomonas syringae</i> pv. <i>syringae</i>	melon seedlings	pepper wastes	plating	-	-	-	15	-	1	-	0.3	-	-	-	Elorrieta et al. 2003
<i>Xanthomonas campestris</i> pv. <i>vesicatoria</i>	melon seedlings	pepper wastes	plating	-	-	-	15	-	1	-	0.3	-	-	-	Elorrieta et al. 2003
<i>Ralstonia solanacearum</i>		plant residues	bioassay	-	120	12	-	-	-	-	-	-	-	-	Date et al. 1993
<i>Ralstonia solanacearum</i>		water	plating	-	-	2	-	0.1	-	-	-	-	-	-	Termorshuizen et al. 2003
<i>Botrytis cinerea</i>		geranium leaves	plating	-	504	-	168	-	-	-	-	-	-	-	Hoitink et al. 1976
<i>Fusarium oxysporum</i> f.sp. <i>melonis</i>		Veg. residues	plating	-	-	288	-	80	-	1	-	-	-	-	Suarez-Estrella et al. 2003
<i>Macrophomina phaseolina</i>	mycelium	cellophane	plating	-	-	-	2	0.2	0	-	-	-	-	-	Bega & Smith 1962
<i>Macrophomina phaseolina</i>	mycelium	PDA	plating	-	-	-	48	24	-	-	-	-	-	-	Mihail & Alcorn 1984
<i>Rhizoctonia solani</i>	micro-sclerotia		plating	-	-	48	10	8	0.5	-	-	-	-	-	Grushevoi et al. 1940
<i>Rhizoctonia solani</i>		barley seed	plating	-	1176	-	168	-	-	-	-	-	-	-	Hoitink et al. 1976
<i>Sclerotinia sclerotiorum</i>	sclerotia		plating	-	-	36	-	1	-	-	-	-	-	-	Grushevoi et al. 1940

<i>Sclerotinia sclerotiorum</i>	sclerotia		plating	-	-	-	936	-	-	-	96	-	-	-	Hermann et al. 1994
<i>Sclerotium cepivorum</i>	sclerotia		plating	192	192	12	6	-	-	-	-	-	-	-	McLean et al. 2001
<i>Sclerotium cepivorum</i>	sclerotia		plating	-	-	41	19	-	-	-	-	-	-	-	Adams 1987
<i>Sclerotium rolfsii</i>	mycelium	PDA	plating	-	-	-	6	3	-	-	-	-	-	-	Mihail & Alcorn 1984
<i>Thielaviopsis basicola</i>	chlamydo-spores		plating	-	115	48	-	24	6	5	4	1.5	-	-	Grushevoi et al. 1940
<i>Thielaviopsis basicola</i>	mycelium		plating	-	-	15	0	-	-	-	-	-	-	-	Pullman et al. 1981
<i>Verticillium albo-atrum</i>	hop vine		plating	-	168	12	3	1	0.3	-	-	-	-	-	Talboys 1961
<i>Verticillium albo-atrum</i>	mycelium		plating	-	-	-	-	0.1	0.1	0.02	-	-	-	-	Miller & Stoddard 1956
<i>Verticillium dahliae</i>	mycelium		plating	-	-	8	2	-	-	-	-	-	-	-	Pullman et al. 1981
INCUBATOR or WATER BATH/ Oomycetes															
<i>Phytophthora cinnamomi</i>	mycelium	agar	plating	-	-	1	0.3	-	-	-	-	-	-	-	Gallo et al. 2007
<i>Phytophthora nicotianae</i>	mycelium	agar	plating	-	100	3.3	1.3	0.1	0.1	-	-	-	-	-	McGovern et al. 2000
<i>Pythium ultimum</i>	mycelium		plating	-	-	9	0.6	-	-	-	-	-	-	-	Pullman et al. 1981
INCUBATOR or WATER BATH/ Viruses															
<i>Cucumber green mottle</i>	residues		bioassay	-	-	-	840	-	-	-	72	-	-	-	Avgelis et al. 1992
<i>Tobacco mosaic</i>	plant juice		bioassay	-	-	-	-	-	-	-	528	-	0.3	0.17	Broadbent 1965

Consultation copy

**Waste & Resources
Action Programme**

The Old Academy
21 Horse Fair
Banbury, Oxon
OX16 0AH

Tel: 01295 819 900
Fax: 01295 819 911
E-mail: info@wrap.org.uk

Helpline freephone
0808 100 2040

www.wrap.org.uk

