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Assessment of potential methods of treating plant containers.

Introduction

The withdrawal of methyl bromide as a means of 'sterilising' used plant containers has prompted a search for alternative methods of achieving the same ends.

The possibilities for replacement treatments for methyl bromide fumigation fall into three categories; alternative fumigants, disinfectants and the use of heat.

The purpose of this document is to review each of the above categories of alternatives to methyl bromide fumigation and to propose treatments to be included in experimental assessments.

Assessments

1) Alternative fumigants

There have been a number of fumigants suggested as methyl bromide alternatives for soil sterilisation. The most promising include methyl iodide, InLine and Telopic. InLine and Telopic are mixtures of 1,3 dichloropropene and chloropicrin. However none of these are currently registered in this country.

For the present study only fumigants with current registration will be considered. Chloropicrin (Nitrotrichloromethane, CCl_3NO_2) is selectively toxic to common root destroying fungi but does not control other soil-borne pests and so would not be a suitable methyl bromide replacement in this case. Telone (1,3 dichloropropene) is used for the control of plant parasitic nematodes in soil but is not effective against fungi and plant diseases.

Only two fumigants with the potential to control the range of pests that may be present in used plant containers have registration in this country. These are phosphine and sulphuryl fluoride. Phosphine is available in a number of solid formulations that produce phosphine from the action of atmospheric moisture on metallic phosphide. Sulphuryl fluoride is available form Dow Agroscience under the trade name of Profume.

Phosphine
Aluminium and magnesium phosphide products are available for rodent control and the fumigation of stored products. These react with atmospheric moisture to produce phosphine gas, which is effective against insects and nematodes. *Frankliniella occidentalis* is controlled by 2 g m^{-3} of phosphine in 16 hours. Phosphine is known to be phytotoxic and it is claimed that it has an anti-fungal effect, but the dose needed to control fungi and weed seeds is not known.

Sulphuryl fluoride
Sulphuryl fluoride is available in the United Kingdom as Profume, for the fumigation of flour mills. Sulphuryl fluoride is effective against invertebrates and a previous study undertaken at CSL showed that it had a phytotoxic effect, but like phosphine the dose needed to control fungi and weed seeds is not known.

Recommendations

Phosphine and sulphuryl fluoride should be tested for their suitability as cleaning and disinfecting agents for use in the recycling of nursery equipment.

2) <u>Disinfectants</u>

There exists a wide range of disinfectant and biocide products that may be suitable for the cleaning and disinfection of nursery hardware such as plant pots and propagation trays. To simplify what is an apparently complex situation these can be grouped according to their active ingredients. These groups are summarised in Table 1 below, which has been modified from information previously included in HDC Factsheet 15/05:

Table 1. Types of disinfectant grouped according to the chemistry of the active ingredient (modified from HDC Factsheet 15/05).

Class	Subclass	Examples	Commercial products
Alkali	Hydroxide	Sodium hydroxide, calcium oxide	
Biguanide	Chlorhexidine		Nolvasan, Virosan
Cationic Surfactant	Quaternary Ammonium Compounds (QACs)	Benzalkonium chloride & other compounds	Antec Ambicide, Hortisept, Menno Ter Forte, Vitafect
Halogens & halogen-releasing compounds	Active chlorine	Sodium hypochlorite; Organic chlorides (eg sodium dichloroisocyanurate); chloramine.	Bleach
	Iodophor		Antec Virudine, Fam 30, Deosan Iodel FD
Halogenated tertiary amine	Halogenated tertiary amine		Avisafe, Trigene
Organic acid	Aliphatic acid	Citric acid	
	Aromatic acid	Benzoic acid	Menno Florades
Oxidising agents	Peroxides	Hydrogen peroxide Peroxyacetic acid	Antec Hyperox Jet 5, Sanpox P, GeoSil
	Peroxygen compounds		Virkon S
	Chlorine dioxide		Purogene
Phenols	Phenolics (high boiling tar phenols)	Carbolic acid, cresylic acid.	Farm Fluid S, Longlife 250S
	Synthetic phenol	Hexachlorophene, triclosan	
	Chlorophenol	Dichlorophen	Panacide M, Enforcer
Reducing agents	Aldehydes	Glutaraldehyde Formaldehyde	Horticide, Unifect G Formalin, Dynaform
Other	Plant extracts	Grapefruit seed extracts Essential oils	Citrox P

The ideal materials for cleaning up recycled nursery hardware should possess a number of properties, including the following:

- Broad spectrum of activity on fungi, bacteria, viruses, invertebrates and weed seeds
- Rapid action against pathogenic organisms
- Effective in the presence of organic matter contamination
- Safe for operators
- Free from unwanted side effects such as corrosiveness, staining and odour production
- Easy disposal of used material without environmental effects
- Convenient
- Cost effective

None of the materials in Table 1 is likely to possess all of the ideal properties, and in some cases there is insufficient information available to be able to make a sound judgement. However, it is possible to summarise the available information. This is done (below) by considering each of the active ingredient groups in turn.

Alkali – hydroxide
Products containing hydroxides, such as Antec Biosolve (which contains sodium hydroxide), are general biocides that will kill all living organisms. The caustic action of such materials is rapid and these products are effective degreasers. They are also efficient in the presence of organic matter, which they readily penetrate. They are corrosive and pose a significant hazard to operators, requiring eye protection and protective clothing during use. Small quantities of diluted solutions may be disposed of by flushing away with water, with the permission of the appropriate waste water authority. Sodium hydroxide is cheap and readily available.

Biguanide – chlorhexidine
Chlorhexidine is used mainly in hand washes, oral hygiene products and as a medical disinfectant in Britain. It is available for general disinfection elsewhere. Chlorhexidine is bactericidal, but not against spores. It will control some fungi, though again activity against spores is poor. There is no information available on the control of nematodes or weed seeds. Action is rapid, requiring contact times on clean surfaces of one minute minimum. Chlorhexidine is inactivated in the presence of organic matter. Products are not corrosive, do not stain and are safe for operators without a requirement for protective clothing. The absence of general disinfection products in Britain prevents comments on cost-effectiveness and convenience.

Cationic surfactants – Quaternary Ammonium Compounds.
Some QAC products (Ambicide, Hortisept, Menno Ter Forte, Vitafect) are formulated for use in horticulture. The products are claimed to control bacteria, bacterial spores, fungi, fungal spores and algae. They may be less effective in the presence of organic matter. The addition of glutaraldehyde (Vitafect PepMV) is necessary to control viruses. Ambicide was less effective than most products from different a.i. groups tested for the control of stem nematode *in vitro* (BOF 49). There is no available information on the control of weed seeds. In general effects improve with increasing contact time. Minimum contact times can be quite short; a 3-minute dip is recommended for treating hatching eggs, for instance. Products are relatively safe for operators, are low-odour or odourless and do not stain. Small quantities of diluted material can be flushed away with the permission of the appropriate waste water authority. Products are readily available but may be more expensive than some competing products.

Halogen-releasing compounds – active chlorine
Examples include household bleach (sodium hypochlorite), organic chlorides (e.g. sodium dichloroisocyanurate) and chloramine. These compounds release the active principle, chlorine gas, in solution. Chlorine has rapid activity against bacteria, fungi and viruses, slower action against spores. Organic matter rapidly consumes available chlorine, incidentally producing trihalomethanes and other potentially carcinogenic compounds, so chlorine-releasing compounds are inefficient in the presence of organic matter. Sodium hypochlorite is corrosive, and both sodium hypochlorite and organic chlorides will release toxic chlorine gas in the presence of acids. These materials however can be, and are, safely handled in their concentrated and diluted forms. Chlorine readily evaporates from water, but any trihalomethanes produced by contact with organic matter may remain. Disposal of volumes of used hypochlorite solution may require input from a specialist contractor, though small quantities could be disposed of by flushing away with the consent of the appropriate water authority. Sodium hypochlorite in particular is readily available and inexpensive.

Halogen-releasing compounds – iodophor
Iodophor disinfectants are acidified solutions of polyethoxylated alcohol and iodine. They are broad spectrum disinfectants, with government approval for the control of bacteria and viruses in the livestock industry. Fungi are also controlled. In two separate trials, iodophor disinfectants proved to be the most effective in a range tested at controlling stem nematodes *in vitro.* Iodophors have a rapid action and can remain effective in the presence of organic matter despite the loss of some activity. Personal protection is necessary when handling the concentrate but the diluted product is easy to handle and at low dilutions drinking water can be treated, indicating its safety. The phosphoric acid content of iodophors can result in corrosion of aluminium, and porous metals, plastics and wood can be stained. Diluted disinfectant has a mild iodine odour, has detergent properties and the depth of its yellow colour provides an indication of the level of activity of the product. Disposal is by treatment with a mild alkali and then flushing to waste with plenty of water. This is likely to require the approval of the appropriate water authority. Products are readily available and are used in a dilute form so are a reasonable economic proposition.

Halogenated tertiary amine
Products, e.g. Trigene Advance, are available for hygiene purposes in the pet and livestock industries and general environment. They are claimed to be virucidal, fungicidal, bactericidal, mycobactericidal and sporicidal. There is no information on the effects of halogenated tertiary amines on invertebrates or weed seeds. Despite detergent action, products should be used as surface treatments after organic contamination has been removed, so activity in the presence of contamination is in doubt. Halogenated tertiary amines are safe for operators to use and can be used on most surfaces without problems of corrosion or staining. Small quantities can probably be disposed of by dilution and dispersal to soil or septic tank. Disposal of larger quantities would be a matter of consultation with the appropriate water authority. Products are readily available, aimed chiefly at the medical market.

Organic acid – Aliphatic acid
Citric acid is a widely-available commodity chemical with activity on a number of bacterial, viral and fungal pathogens. It is used as an antimicrobial agent in home brewing, for instance. It is also claimed to suppress algae. Citric acid was used for general disinfection during the 2001 outbreak of foot and mouth disease. It is classed as an irritant in concentrated form but is a natural component of cirus fruits and is not harmful to operators or the environment when diluted. Citric acid is not corrosive to

most materials and does not stain or smell unpleasant. Small quantities can be diluted and flushed away with the consent of the appropriate water authority. Citric acid is a commodity chemical and is therefore cheap and easy to obtain.

Organic acid – Aromatic acid
Benzoic acid, an aromatic acid, is the active ingredient in Menno Florades, a horticultural disinfectant. Benzoic acid is active against bacteria and fungi, and has variable activity against viruses. In tests on the control of stem nematodes *in vitro* (BOF49) benzoic acid was second only to the iodophors and retained some of its activity in the presence of soil contamination. It is safe for operators and though it may corrode unprotected metals this does not seem to be serious enough for it to be unacceptable to growers. UK information on this product is currently difficult to come by and its availability in the UK is in some doubt.

Oxidising agents – peracetic/peroxyacetic acid
Examples include Antec Hyperox, Jet 5, Sanpox and GeoSil (which includes a silver synergist). In solution these disinfectants produce peracetic acid by the action of hydrogen peroxide and acetic acid. Peracetic acid kills bacteria, fungi and viruses, including spores. Peracetic acid products have had mixed effects on nematodes; in BOF 49 they proved less effective than most other materials tested in controlling stem nematode *in vitro*, but when tested in hot-water treatment for the control of stem nematode in narcissus Jet 5 was considered effective. There is no information on the control of insects and weed seeds. Hydrogen peroxide products can be corrosive and can even form explosive compounds in the concentrated state, but are less potentially harmful when diluted. Peroxyacetic acid has a pungent odour. The breakdown products of hydrogen peroxide are water and oxygen and therefore present no disposal problems but peracetic acid has significant aquatic toxicity. Products are widely available and reasonable in cost.

Oxidising agents - peroxygen compounds
Virkon S is a typical product and is a blend of peroxygen compounds and organic acids. This has a wide spectrum of activity on bacteria, viruses, fungi and spores. Activity on invertebrates and weed seeds is unknown. It is rapid in action and is active in the presence of organic contamination. The diluted product is very safe for operators and the environment and does not stain, corrode or have an unpleasant odour. The product is widely available and reasonably costed.

Phenols – high boiling tar phenols
High boiling tar phenols are broad-spectrum biocides with rapid action, which control bacteria, viruses, mycoplasmas and fungi. Though activity may be reduced in the presence of organic matter HBTA's remain effective, more so than many other materials. They are however acidic, can be corrosive and stain some substrates. HBTA's have a strong antiseptic odour and may be less pleasant to handle than some other biocides. Some products have a high acute toxicity to fish and aquatic invertebrates. Disposal of used, diluted product will require consultation with the local water authority. Products are cheap and widely available.

Phenols – synthetic phenol
Hexachlorophene and triclosan are synthetic phenols. These are not as broad spectrum in activity as HBTA's, with limited fungicidal and virucidal activity. They are normally used in the absence of organic matter, so activity in the presence of soiling may be in some doubt and activity is also reduced in hard water. Synthetic phenols have less odour than HBTA's and are less prone to staining. There are question marks over environmental toxicity and safety of hexachlorophene.

Phenols – chlorophenol
The active ingredient of chlorophenol products is dichlorophen. These products are sold for the control of moss, algae, fungi and bacteria on hard surfaces, glasshouse structures and managed amenity turf. As registered pesticides there are strict limitations over methods of use and these include requirements for protective clothing and preventing access by unprotected persons for 48 hours after treatment or until surfaces are dry. Dichlorophen is considered dangerous for the environment and very toxic to aquatic organisms. Disposal of unused diluted product would be likely to require the use of a specialist contractor. Products are readily available.

Reducing agents – aldehydes
This category includes glutaraldehyde and formaldehyde. Both are broad-spectrum biocides but tend to require a long contact time. The action of these materials is temperature dependent, with formaldehyde for instance being effective at controlling stem nematodes at the temperatures used in hot-water treatment (ca. 45°C) but much less effective at ambient temperatures (BOF49). The aldehydes are inactivated by the presence of organic matter. Glutaraldehyde is irritant, can cause skin and lung sensitisation and may be mutagenic: formaldehyde is toxic by contact or inhalation, may be carcinogenic and is corrosive. Formaldehyde has a mousey odour and is difficult to work with. Formaldehyde is a very cheap commodity chemical. Glutaraldehyde is available as formulated products and is more expensive.

Plant extracts
There are a number of products based on plant essential oils or extracts of citrus seeds. The most prominent of these is Citrox P, a citrus seed extract which is available in the UK and is recommended for use in cleaning recycled pots and trays in horticulture. Bacteria, fungi and viruses are all controlled by Citrox P but the product is not insecticidal. Citrox P is considered harmless to operators and does not corrode or stain surfaces. Disposal of used diluted product should not present a problem.

Conclusions

- Many product types have potential for the control of the wide range of pathogenic organisms that might persist on nursery hardware.
- Tests on these products have often included bacteria, viruses, mycoplasmas and fungi (including spores) of human and animal health importance rather than organisms pathogenic to plants.
- Products may be unsuitable for use in recycling used pots, trays etc for one or more reasons. These include:
    - Narrow spectrum of activity
    - Inability to cope with organic soiling
    - Unpleasant odour
    - Tendency to stain
    - Corrosiveness
    - Inadequate operator safety
    - Environmental hazard
    - Problematical disposal of unused diluted material
    - Expense
- Some product types are worthy of a further exploration of their properties.

Recommendations

Following this review, the following product types should be tested further for their suitability as cleaning and disinfecting agents for use in the recycling of nursery equipment:

- Halogen-releasing compounds – iodophor. E.g. Antec Virudine, FAM 30.
- Halogenated tertiary amine. E.g. Trigene Advance
- Organic acid – aliphatic acid. Citric acid.
- Peracetic/peroxyacetic acid. E.g. Jet 5, GeoSil.
- Peroxygen compounds. Virkon S.
- Plant extracts. E.g. Citrox P.

Products should be tested at the manufacturer's recommended concentration. Test organisms will be exposed to the products for durations of 10 minutes and 60 minutes.

The following are not recommended for further testing at this stage (reasons given in brackets):

- Alkali – hydroxide (corrosive; operator hazard)
- Biguanide (narrow activity spectrum; inactivated by organic matter)
- Quaternary ammonium compounds (poor activity on viruses and nematodes; reduced activity in the presence of organic matter)
- Hydrogen-releasing compounds – active chlorine (Inefficient in the presence of organic matter)
- Organic acid – aromatic acid. Benzoic acid. (Doubtful availability in the UK at present)
- Phenols – HBTA. (Acidic, corrosive, strong odour, likely to stain, dubious environmental safety)
- Phenols – synthetic. (Limited activity. Environmental toxicity and safety concerns)
- Phenols – chlorophenol. Dichlorophen. (Registered pesticide with limits on methods of use)
- Reducing agents. Glutaraldehyde and formaldehyde. (Temperature dependent activity; Operator safety)

3) Heat treatments

Heat treatments that successfully replace methyl bromide as a means of sterilising nursery hardware (e.g. pots, propagation trays etc.) will need to control a wide range of organisms that are capable of damaging plants, and they will have to do so without damaging the hardware itself. The nursery hardware most susceptible to heat damage is that made from plastics, as these are generally more susceptible than other materials such as metal, wood and ceramics. Most plant pots are made from polypropylene (polypropene), which has a melting point of 160°C and, although it can be steam sterilised, a long-term service temperature of only 80°C. Trays are more likely to be manufactured from polystyrene, which loses its mechanical stability between 80°C and 120°C and can only be safely used at temperatures up to 70°C. This upper temperature limit for polystyrene is likely to be the limiting temperature for any heat treatment that is to be applied universally to nursery hardware for the control of plant pathogens.

Generally speaking, heat applied via a 'wet' carrier such as hot water or steam is more effective in controlling pathogens than heat applied 'dry' as in an oven, perhaps because organisms kept dry have very little metabolic activity and are therefore less susceptible to damage, or perhaps because there are differential heat transfer effects between the two systems. For this reason much of the work on the effect of heat on pathogens has been done on the use of hot water treatment (HWT), where the heat has been applied by immersing the subject material into a water bath maintained at the chosen temperature, or on the use of steam/air mixtures, where the air is used as a means of modifying and making more controllable the effective temperature of the steam. However, there is some information on the use of dry heat to disinfest buildings such as flour mills. There has also been some interest in the use of microwave energy to kill pathogens and weed seeds.

There is a large and complex literature on the use of heat to control various plant-pathogenic organisms. The variables that affect the efficacy of heat treatments include; the nature of the organism to be controlled, the nature of the substrate in/on which the organism is to be found, the temperature selected and the duration of the treatment. The following is a brief summary of some of the information that is available about each type of pathogenic organism.

Arthropods (including insects).

The major use of heat to control arthropods has been on non-perishable goods, including stored products (MBTOC, 2002).

- Exposure to a temperature of 65°C for 1 minute is said to be sufficient to control all stages of all stored products insects.
- The tobacco industry uses heat to kill larvae of the cigarette beetle *Lasioderma serricorne* in tobacco. The larvae are controlled by exposure to 60°C for 3 minutes, 55°C for one hour or 50°C for 3 hours.
- Flour mills are disinfested by heating the whole structure to a temperature of 50°C for 20-30 hours.
- Large narcissus fly (*Merodon equestris*) and bulb scale mite (*Steneotarsonemus laticeps*) in narcissus bulbs are both controlled by hot water treatment at 43°C for 1 hour.
- On strawberry runners, immersion in hot water at 46°C for 10 minutes kills the strawberry tarsonemid *Phytonemus pallidus* ssp *fragariae*, the two-spotted spider mite *Tetranychus urticae* and the strawberry aphid *Chaetosiphon fragaefolii*.

Nematodes

As might be expected, it takes longer to kill nematodes that are endoparasitic in bulky plant organs than it does to control those that are surface-dwelling or inhabit the superficial layers of plant tissues. Thus, it takes 3 hours exposure to either 44.4°C or 46°C (depending on pre-treatment conditioning) to control stem nematode, *Ditylenchus dipsaci*, in narcissus bulbs, with much of the exposure period being necessary to raise the temperature of the plant tissues to the desired level. However, stem nematode in strawberry runners, which are much less bulky than narcissus bulbs or gladiolus corms, is killed by hot-water treating the runners at 46°C for only 10 minutes.

- Treatment at 43.5°C for 4 hours will control potato tuber nematode (*Ditylenchus destructor*) in gladiolus corms.
- Bud & leaf nematodes (*Aphelenchoides* spp.) are ectoparasites within buds or are endoparasites in thin tissues such as leaves. In water, these nematodes are killed by exposure to 43.3°C for 20 minutes or to 46°C for 5 minutes.
- In potted Begonias the same nematodes have been killed by immersion of the plant and pot in water at 46.7°C for 3 minutes, 47.8°C for 2 minutes or 49°C for 1 minute.
- Chrysanthemum stools have been freed of bud & leaf nematode by immersion in hot water at 46°C for 5 minutes.
- Cysts of potato cyst nematode are killed by exposure to 47.8°C for 30 minutes, 50°C for 10 minutes, 55°C for 1.5 minutes or 60°C for 30 seconds.
- Soil solarization (natural heating of soil following covering with a plastic mulch) has also been used to control several species of nematode, including root lesion nematodes (*Pratylenchus* spp.) but the actual temperature/time combination that is lethal is difficult to pinpoint.
- In Convallaria, the root lesion nematode *Pratylenchus convallariae* has been controlled by hot water treatment at 43.5°C for 60 minutes or 45°C for 30 minutes (Germany), and in Japan it was found that treatment at 47°C for more than 30 minutes completely controlled the nematode.

Fungi

Though much heat treatment is applied to plant material to control pests, particularly endoparasitic nematodes, there is nevertheless a good deal of information on the temperature/time exposures required to control fungal diseases of plant tissue, much of it from the literature on hot water treatment.

- Heating gladiolus corms to 57°C for 30 minutes (Israel) or 55°C for 30 minutes (France) is sufficient to rid them of *Fusarium*.
- 53-55°C for 30 minutes is sufficient to kill *Botrytis, Stromatinia* and *Fusarium* in cormlets of gladiolus (which are smaller than the corms) though if *Fusarium* is a particular problem raising the temperature to 55-57°C is recommended, despite the fact that some plant damage may occur.
- 57°C for 30 minutes is also recommended to control *Fusarium* in bulbous iris and Strelitzia seed.
- *Fusarium oxysporum* was eradicated from garden stocks by steam/air treatment at 54°C for 15 minutes.
- *Fusarium oxysporum f.sp.dianthi* has been controlled by exposure to microwave energy at 2450 Mhz for 60-90 seconds.
- *Phytophthora* on grapevine can be controlled by treating at 50°C for 15 minutes.
- 10 minutes at 43.3°C is sufficient to control mint rust (*Puccinia menthae*) in mint.
- The incidence of downy mildew in shallot sets is reduced when the sets are treated at 43.5°C for two hours.

Many treatments are directed at reducing fungal infections of various seeds.

- Brassica seed treated at 50°C for 18 minutes is freed of *Alternaria*, whereas extending the time to 25 minutes exposure will also control *Phoma lingam.*
- *Septoria* on celery seed is controlled by hot water treatment at 50°C for 25 minutes or steam/air treatment at 56°C for 30 minutes.
- On lettuce seed, *Septoria* is controlled by HWT at 48°C for 30 minutes.
- The following treatments control *Ustilago nuda* (loose smut) on cereal seed: barley - 37°C for 6 hours, 40°C for 4 hours, 43°C for 2 hours; wheat – 40.5°C for 5 hours, 43.5 for 3.5 hours, 46 for 2 hours, 49°C for 1.5 hours.
- *Alternaria* on Zinnia seed was controlled by hot water treatment at 52°C for 30 minutes
- Control of *Alternaria* on China aster requires exposure to 53°C for 30 minutes.
- *Itersonilia* on parsnip seed is controlled by treatment at 45°C for 30 minutes, though germination may be reduced.
- *Verticillium dahliae* and *Didymella* on tomato are controlled by exposure to 45-50°C for 30 minutes.

Bacteria

Hot water treatment has been relatively little used to control bacterial diseases of plants.

- *Xanthomonas* on brassica seed is known to be controlled by hot water treatment at 50°C for 25 minutes or by steam/air heating at 54°C for 30 minutes.
- Hot water treatment at 56°C for 10 minutes controlled bacterial blight in garden stocks.
- *Pseudomonas syringae* is controlled by hot water treatment at 52°C for 6 minutes.

Viruses

Heat treatment is not frequently used to control virus diseases in plants, though it is sometimes a component, along with meristem culture, of a system designed to produce virus-free material from an infected mother stock.

- Vegetable seeds have been treated with heat to prevent infection with tobacco mosaic virus found as a contaminant on the seed coat. Dry seed has to be exposed to dry heat for either 2-4 days at 70°C or 1 day at 80°C.

Weed seeds

Many of the treatments described above are intended to control pathogenic organisms on living plant material without seriously damaging the plants themselves. It seems to be the case, therefore, that plant material is more resistant to heat damage than most pathogens. If this is true, then the degree of exposure to heat necessary to control weed seeds is likely to be greater than that required to control other organisms.

Regulated heat has not often been used to control weed seeds. Where heat has been used, it has generally consisted of exposing the material to very high temperatures for brief periods, as in the use of flame weeders in organic agriculture.

Dry seed is capable of withstanding long-term exposure to dry heat at quite high temperatures. For instance, wheat seed is apparently unaffected by exposure to 70°C for 7 days, though the germination of barley subjected to the same regime drops slightly. Some species, originating from regularly-burned savanna woodlands and grassland, will even tolerate exposure to 200°C for 5 minutes. In tests on weed seeds in dry soil (2% moisture), nearly all seeds tested were viable after 7 days exposure to 60°C, and even at 70°C it required 2 days exposure to significantly decrease viability. However, in moist soil (19% moisture) 6 hours exposure to 60°C was sufficient to kill most seeds.

With the increasing popularity in some parts of the world of soil solarization as a means of controlling weeds and pathogens in field soils there has been recent work on the exposure criteria necessary to kill the seeds of some weeds. In California, seeds of all weeds tested (London rocket, black nightshade, annual sowthistle, barnyardgrass, common purslane and tumble pigweed) were killed by exposure to 70°C for 20 minutes, with London rocket, barnyardgrass and annual sowthistle failing to survive 10 minutes exposure at this temperature. At 60°C, London rocket, barnyardgrass and annual sowthistle were dead within 15 minutes, tumble pigweed within an hour, black nightshade within 2 hours and common purslane within 3 hours. At 50°C death occurred in the exposure range 4 hours (annual sowthistle) to 113 hours (tumble pigweed) and at 46°C this range became 15 hours (annual sowthistle) to 13 days (tumble pigweed). In Florida, for most of the weed seeds studied, 3 hours exposure to 60°C was sufficient to reduce germination to 0%.

There is relatively little information on the effects of exposure of weed seeds to microwave energy. When used on soils, microwaves are relatively ineffective at killing weed seeds because the waves do not penetrate the soil to a very great depth. However, some seeds have been killed by treating in a microwave oven for as little as 45 seconds.

Conclusions

- Heat treatment temperatures higher than 70°C are at risk of causing some damage to horticultural plastics.
- Heat applied ‘dry’ (e.g. as in an oven) is likely to be less effective than the same level of heat applied ‘wet’ (e.g. as in a hot-water bath or steam/air blending system).
- Weed seeds are likely to require higher temperatures and/or longer exposures than most plant pathogens in order to kill them.
- Lower temperatures require disproportionately-longer exposures than higher temperatures in order to control plant pathogens and weed seeds.
- Higher temperatures applied for shorter times are likely to have a lower overall energy cost than lower temperatures applied for longer.
- Microwave energy may not penetrate very deeply into soils but there may be some merit in using microwaves to kill contaminants on the surface of nursery hardware.

Recommendations

Experiments in controlling pests, pathogens and weed seeds with ‘wet’ heat should be done at four different temperatures (50, 60 and 70°C) over a range of exposures (10, 30, 60 minutes)

Experiments with ‘dry’ heat should also be done at 50, 60 and 70°C, even though it takes more than a day at 70°C to kill some weed seeds. Temperatures higher than this are likely to damage the materials being treated. Exposure times of 10, 30 and 60 minutes are recommended.

Experiments with microwave energy require short treatment times, from 10-second exposures up to 2 minutes maximum.