Project Title:	**Development of a low-cost pilot test procedure for assessing the efficacy of slow sand filtration on individual nurseries.**
Report:	**Final Report (March 2000)**
Project Number:	**HNS 88a**
Project Leader:	**Dr. Tim Pettitt** **HRI Efford** **Lymington** **Hants SO41 0LZ**
Previous Reports:	**HNS 88**
Key Workers:	**Tim Pettitt** — **Plant Pathologist HRI Efford** **Paul Newnham** — **Maintenance Supervisor** **John Gardiner** — **Maintenance Staff** **Mike Wainwright** — **Assistant Pathologist** **Jenny Miller** — **Assistant Pathologist** **Glyn Evans** — **Maintenance Staff**
Location:	**HRI Efford, Lymington, Hants SO41 0LZ** **Commercial nurseries in St. Ives, Huntingdonshire, Evesham and Droitwich, Worcestershire**
Project Co-Ordinators:	**Mr. Richard Oliver, Anglia Alpines and Herbs Ltd., St. Ives Road, Somersham, Huntingdon, Cambs PE17 3ET** **Dr. Hugh Nunn, Orchard Close Nursery, Village Street, Harvington, Evesham, Worcestershire WR11 5NQ**
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CONTENTS

Within this report SSF may variously be read as Slow Sand Filter or Slow Sand Filtration

FOREWORD BY PROJECT CO-ORDINATOR

Nursery water can be full of fungal nasties. *Phytophthora*, *Fusarium* and *Pythium* are widely found in water sourced from lagoons, roofs, rivers and drainage channels.

This project looked at cleaning up water on three commercial nurseries and the preliminary water examination showed up all sorts of horrors – all good reasons for cracking on and getting the water sorted.

Funded by H.D.C., Tim Pettitt and his Efford team have done a great job in leading the way, injecting impressive doses of science and then showing us how to do it!

The basic process seems almost too simple – run dirty water down a sand column of the right type and friendly micro-organisms will zap the nasties. And, hey-presto, out of the bottom flow rivers of pathogen-free water, which is fit for nursery use. Amazing!

This report tells you how its done. The whole thing seems simple but a good installation costs a bit and has to be planned. However, we have a nursery tool here which is worth looking at and it is underpinned by good research and accessible people who will provide advice.

This is but one example of how your money is being put to good use.

H.L. Nunn
Project Co-ordinator

PRACTICAL SECTION FOR GROWERS

Background

Water is easily contaminated with plant-threatening fungi. *Pythium Phytophthera* and *Fusarium* are examples of pathogenic fungi found in many untreated water sources on plant-growing nurseries. Nurserymen ignore them at their peril!

Cleaning up contaminated water can be done in a number of ways and this report sets out to show what can be achieved with Slow Sand Filtration (SSF). Passing contaminated water through a sand column with certain specified characteristics, results in the removal of deleterious fungi and an uncontaminated flow of safe water.

It follows that clear financial benefits might accrue from adopting this 'low-cost' methodology and one which is environmentally friendly as no chemicals or high energy sources are required.

Comparative trials funded by MAFF at HRI Efford identified SSF as a promising technique for use in the HNS sector because of its flexibility in terms of size and design and its relatively low cost. Strategic studies of SSF funded by MAFF at Efford have demonstrated that a significant part of SSF action is biological, and that under extreme conditions (e.g. autoclaving or excessively fast filtration flow rates) this can break down. This work has led to improvements in pathogen detection, and these allow very accurate quantitative, as well as qualitative, assessments of SSF performance. These techniques were successfully used in HDC-funded work (HNS 88) to monitor the commercial development of two full-scale HNS-based SSFs, each capable of treating approximately 200 m^3 day^{-1}.

Objectives

The use of SSF to remove plant pathogens from irrigation water is still a new technology. On a commercial scale, the installation of a new SSF invites a number of questions to which tentative answers can now be given:

For example:

Which locally available sands might be suitable?

How quickly will a filter become effective (i.e. develop an active biofilm layer over the sand grain surfaces) under local conditions?

How will the operation of the SSF fit into the nursery's programme of work?

Is SFF truly appropriate for the site in question?

Any new technology or installation carries some financial risk. The objective of this project was to minimise this risk by developing a simple low-cost system for sand-based filtration which would:

i) identify pathogenic fungi present in existing nursery supplies;

ii) measure the filter maturation period;

iii) compare sands for their performance and cost effectiveness;

iv) test flow rates in order to gauge what size of full-scale filter would be required;

v) familiarise staff with the concept and operation of SSF without the risk of contaminating the main water supplies of the nursery.

Summary of Results

Two types of experimental slow sand filters were installed on three commercial nurseries and at HRI Efford.

The first filter rig was designed to simulate the conditions found in a full scale SSF, and to compare a range of different sands.

The second was a simple low-cost small-scale pilot filter, designed for the on-site assessment of the potential of slow sand filtration for the cleaning of irrigation water.

Using the first rig, twelve sands of varying grain size and from widely dispersed quarries were compared for their efficacy. Sands were variously described by growers as 'sharp sand', 'fine sand' or even 'plasterer's mix'. All were lime-free and the majority would probably be suitable for use in Efford sand beds. All sands performed well on all sites at filtration flow rates of 0.1 mh^{-1} and 0.2 mh^{-2} (The surface areas of different SSF vary enormously, so instead of using volumes, flow rates through a SSF are normally quoted as the height of the water column passing through the sand filter with time. This volume can then be easily connected into a volume measurement (m^3) by multiplying by the filter surface area (m^2)). However, at the higher flow rate of 0.3 mh^{-2}, some sands became less efficient. In addition, it was observed that when the filtration flow rate was increased, many filters suffer a temporary loss of efficacy. This suggests that flow rates need to be maintained at a fairly constant level in water to maintain efficiency. In addition, intermittent flows through sand may also risk penetration by pathogenic propagules.

The small-scale, barrel-type, pilot filters proved straightforward to construct and install and worked well on all sites. Results obtained with these small rigs were in agreement with those from the sand comparison rigs, and they were shown to be able to provide all the basic information needed to confidently install a full-scale SSF to a 'site-tailored' specification.

Action Points for Growers

- ***Sand Selection:***

  Sands from widely dispersed quarries appear suitable for SSF so long as they satisfy the basic physical grading requirements. Two parameters are widely used by the water industry to classify SSF sands; these are:

  a) The effective size (ES_{10})
  b) The uniformity coefficient (UC)

  The ES_{10} is the sieve mesh diameter through which 10% by weight of sand will pass. The UC gives an idea of the uniformity of the sand and is calculated by dividing the sieve mesh diameter through which 60% by weight of the sand will pass (ES_{60}), by the ES_{10}. The lower the UC value, the more uniform the sand is. From this project, sand with ES_{10} values of 0.20–0.33 were effective at removing plant pathogens in SSF. UC values up to 4 appeared to be good, but results from this study gave an indication that the lower the UC value was (the more uniform the sand), the better the SSF performance obtained, especially at higher flow rates. In the absence of detailed sieve analysis data (this is normally available from quarries upon request), a good 'rule of thumb' for selecting a sand is to say no more than 10% by weight should be sand grains less than 0.2 mm in diameter and also no more than 10% by weight should be greater than 1.00 mm diameter.

- ***Construction of pilot test rig for SSF testing on nurseries:***

  The basic pilot filter design consisted of a circular 330 litre rainwater-butt (KAR (UK) Ltd, Manchester) with a lid and a simple tap fixed 6 cm up from the base (Figure 1). To the inside of the tap fitting a 55 cm length of 18 mm diameter pvc tubing was attached that had previously been drilled with 7 mm diameter holes at an approximate spacing of 2 cm (all round the diameter of the pipe). This tube (Figure 2) was wrapped in a single layer of nylon mesh (0.3 mm mesh) held in place with four cable ties. In the bottom of the water butt, a layer of gravel (12 mm gravel) was laid up to, and approximately 1 cm above, the perforated tube outflow (Figure 3). On top of this gravel layer, a layer of the test sand was placed to a depth of about 30-40 cm. Water was supplied to this simple filter arrangement via a ½ inch bore ball cock valve, which was placed through the side near the top of the barrel, and arranged to give a water level that provided a water head of at least 40 cm above the sand (Figure 4). In the experimental systems used in this study, untreated water was supplied to the ball cock valves via gravity flow from a header tank designed to supply a series of comparison rigs. However, this would be unnecessarily complex for a straightforward nursery test of SSF and any system of supplying water to the valve would be suitable. The surface area of the filter sand was calculated by πr^2 and the volume of water expected per

hour was calculated by $\pi r^2 h$, where h is the filter flow rate in mh^{-1} (which should be between 0.1 and 0.2 mh^{-1}, although faster flow rates can easily be tried with this apparatus). The pilot filter's flow rate could then be easily set by adjusting the water butt tap to supply the calculated correct volume of water in 30 seconds.

For example, a barrel of 0.5 m radius at a flow rate of 0.15 mh^{-1} and assuming π = 22/7, would produce 22/7 x $(0.5)^2$ x 0.15 m^3 of water per hour.

- ***Installation of pilot filter***

Installation of a pilot filter of the above design is straightforward. The position is decided by the availability of the raw water supply to be treated. Also, a suitable power supply will be needed if an independent pump is to be used to supply raw water to the rig. The pilot filter is simply positioned on a 60x60 cm paving slab, which has been laid and levelled on a layer of builder's sand.

- ***Running of pilot filter***

Running a pilot filter will, as indicated above, provide information on the priming, run times and filter flow rates, possible at an individual nursery. If filter clogging occurs, samples of the material clogging the filter can be collected and analysed in order to assist in deciding on the appropriate type of pre-filtration system to use for an individual site.

- ***Water testing***

Testing of the water for the presence of plant pathogens or 'indicator' species such as water moulds (non-pathogenic relatives of the important plant pathogens *Pythium* and *Phytophtona*) is vital. Ideally, water samples should be tested at the start of the test run and then after 2-3 weeks (expected time for priming to occur) and after 5 weeks (to check for stability of priming). A water testing service, focussed on SSF efficacy, is available at HRI Efford.

Figure 1: General view of barrel-type pilot SSF. (A) shows position of exit tap and (B) shows position of raw water feed to ballcock.

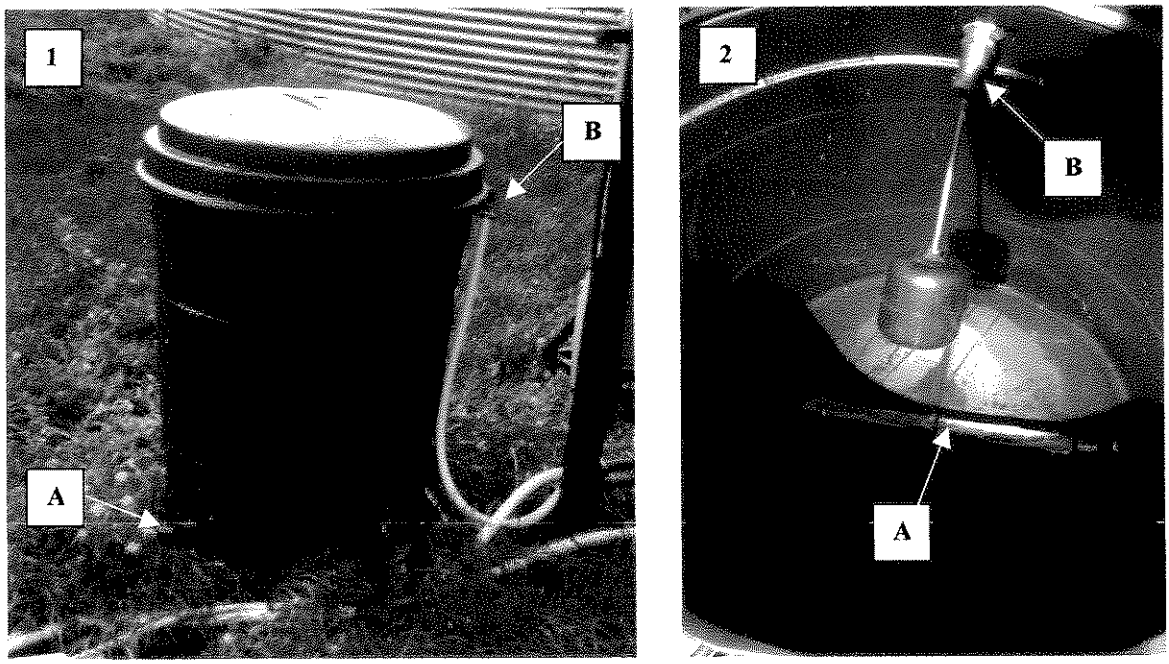


Figure 2: Inside of barrel-type pilot SSF, showing (A) the drainage tube attached to the inside of the tap fitting and (B) the position of the ballcock valve.

Figure 3: Illustration of the gravel drainage layer (A) inside the pilot filter, showing how the sand layer is simply placed directly on top of the gravel (B).

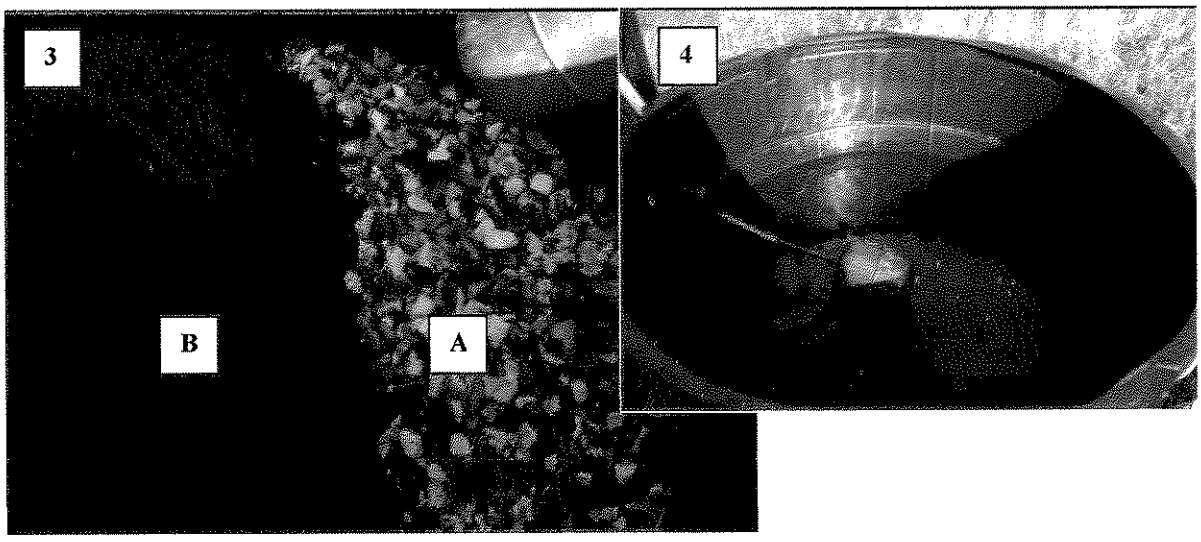


Figure 4: Operational barrel-type pilot SSF, showing maintenance of constant water head over the sand using a ballcock valve.

Anticipated Practical and Financial Benefits

The potential financial benefits of successfully installing slow sand filtration to allow recirculation of irrigation water have been outlined in previous work sponsored by the HDC (HNS 88). The benefits include:

savings in water costs
help in compliance with ever-tighter legislation on water use and disposal
increased flexibility in the management of water supply (especially in periods of drought).

A suitable low-cost set-up for running pilot filters *in situ*, would enable individual growers to carry out low risk feasibility studies and familiarisation exercises on their own nurseries at a target cost of approximately £400-500 (including water testing). This would help with tailoring the SSF design to the particular nursery in question, and would allow a balanced decision on whether to use SSF or not to be made, without incurring the relatively high capital cost of full-scale installation.

After its initial use, a pilot filter rig could be either used for a small section of a nursery away from the main system (e.g. a propagation unit) or stored for future use in testing new or promising filter media (the market already abounds with 'novel' filter media which are claimed, often without substantial evidence, to be more effective than sand), or even new sources of sand.

Further details:

Please request the Science Section of this report from HDC.

SCIENCE SECTION

Introduction

The potential financial benefits of successfully installing slow sand filtration (SSF) to allow the safe recycling of irrigation water, as well as the peace of mind from using the technique to treat potentially contaminated surface-derived waters, have been outlined in a previous HDC-funded report (Pettitt, 1998: HNS 88). These benefits might include savings in water costs, help in compliance with ever-tighter legislation on use and disposal of water, and increased flexibility in the management of water supply (especially in periods of drought).

Comparative trials funded by MAFF at HRI Efford identified SSF as a promising technique for use in the HNS sector because of its flexibility in terms of size and design and its relatively low cost. Strategic studies of SSF funded by MAFF at Efford have demonstrated that a significant part of SSF action is biological, and that under extreme conditions (e.g. autoclaving or excessively fast filtration flow rates) this can break down (Pettitt, 1996). This work has led to improvements in pathogen detection techniques (Wakeham, Pettitt & White, 1997; Pettitt, Finlay, Scott & Davies, 1998), and these allow very accurate quantitative, as well as qualitative, assessments of SSF performance. These techniques were successfully used in HDC-funded work (HNS 88) to monitor the commercial development of two full-scale HNS-based SSFs, each capable of treating approximately 200 m^3 day^{-1}.

The use of SSF to remove plant pathogens from irrigation water is still a new technology. On a commercial scale, the installation of a new SSF always involves a number of questions to which full definitive answers are not yet available:

- Which locally available sands are suitable?
- How quickly and how effectively will the filter mature (i.e. develop its active biofilm layer over the sand grain surfaces) under local conditions?
- How will the operation of the SFF (e.g. frequency of cleaning, which varies considerably with water source) fit into the nursery's programme of work?
- Is SFF best suited to the site in question?

All of these uncertainties introduce a measure of risk when setting up a full-scale SSF. A key objective of this project was to minimise these risks by developing simple, low-cost, small-scale pilot filters which could be used within a nursery context to:

i) measure the maturation period;

ii) compare locally available sands which could be used cost effectively;

iii) test flow rates in order to gauge the size of filter needed for a full-scale operation;

iv) familiarise staff with the concept and operation of SSF without risk of contaminating the main water supplies of the nursery.

Materials and Methods

Construction of pilot test rigs

Two types of test rig were developed, constructed and installed on four sites including the HRI station at Efford):

- A three column rig capable of comparing three different sands simultaneously – see Figure 5.

- A simple 'barrel-type' rig was developed and installed as a low-cost, pilot test apparatus –see Figure 10.

The Three Column Rig

This sand comparison rig was relatively complex, and consisted of three columns made from 160 mm diameter pvc sewer pipes mounted on a welded mild steel tubing frame. The columns were each 3 m long, which allowed for a maximum sand depth of 1 m, with a water head above it of 1.5 m. The bottoms of the columns were sealed with cap fittings (Figure 6) inside which a drilled steel plate (8 mm diameter arranged in a radial pattern at 15 mm spacings) was mounted and overlaid with a nylon mesh (0.3 mm mesh), to hold the filter sand in place and allow free drainage of filtered water from the column. Water was taken from each column via 40 mm diameter pvc pipework which was connected to a vertical transparent tube which could be used to manometrically measure filter head loss (i.e. the resistance to flow offered by the filter). In operation, the transparent manometer tube was normally kept empty, to prevent build up of algae, and could be shut off from the test columns using valves. Care was taken when making head loss measurements, to ensure that the flow into the transparent tube was the same as the SSF flow rate so as not to disrupt the filter sand column. The main flow from the columns was via ¼ inch needle valves (straight wade couplings) inserted into the 40 mm pipes to allow an accurately-regulated exit flow of water and therefore controlled filtration flow-rate. These valves delivered their filtered water to a drainage pipe via flexible 'Tricoflex' tubing connectors (D9 polyester cord-reinforced, 15 mm diameter) which could be easily detached from the drain to deliver water samples into collection bottles.

At the top end of each column, a constant head of water was maintained by a continuous trickle of untreated water balanced by an overflow pipe. The trickle of water was regulated by valve and maintained by gravity flow from a black polythene header tank (Ferham FRL 50, 230 litre), which was mounted at the top of the steel frame (Figure 7). This header tank was also used to supply water to the barrel-type pilot filter which will be described later. Access to the inside of each filter column was gained via hatches mounted on the column fronts (Figure 8). Through these, sand could be placed in columns and the sand surface could also be scraped during filter cleaning operations.

The untreated water supply was different at each site used in the study. These were:

- a river
- a rainwater storage tank
- a large clay-lined reservoir collecting HNS nursery runoff and rainwater
- a small (50 m^3) butyl-lined pond.

Arrangements for delivering water to the filtration rig header tank were therefore different at each site. Also, with exception of the river water where return of treated water was easily achieved by gravity flow, arrangements had to be made to collect and pump treated water back to the source so as to avoid unnecessary depletion of the host nursery's valuable water reserves.

Water was lifted directly from the ***river source*** to the header tank using a submersible pump (Nova 300; max. flow 200 l min^{-1}; max head 7.1 m) which was suspended from an angle iron frame attached to the nursery's existing water abstraction facility. At the site with a ***rainwater*** storage tank, the filter rigs were positioned next to the tank. The pump (Nova 300, submersible) was suspended from a steel boom attached to the comparison rig frame. The boom was constructed from 1" BSP steel tubing and was also used to convey water from the pump to the header tank.

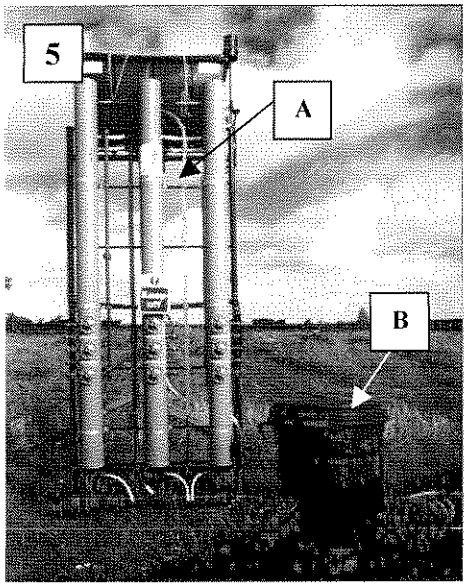
A much larger boom was requited to carry water to and from the test filter rigs across the 15 m wide berm of the ***clay-lined reservoir***. This boom was supported from the filter frame using steel cables attached to welded eyes in a style similar to a suspension bridge. The supply pump (Nova 300, submersible) was suspended from a raft constructed from 110 mm pvc tubing connected in a 1 m square with elbow joints (Figure 9). Using guide cables, the raft was kept clear of the reservoir banks, enabling the pump to extract reasonably clear water.

Arrangements for water collection from the small ***butyl-lined experimental pond*** were more permanent, with a pump (of same type as described above) suspended from a fixed boom supplying a number of outlets, one of which was used to feed water into the header tank of the comparison rig.

The Barrell Filters

The ***barrel-type*** pilot filters were deliberately of a more simple construction. Each filter consisted of a circular 330 l rainwater-butt (KAR (UK) Ltd, Manchester) with a lid and a simple tap fixed 6 cm up from the base (Figure 10). To the inside of the tap fitting a 55 cm length of 18 mm diameter pvc tubing was attached that had previously been drilled with 7 mm diameter holes at an approximate spacing of 2 cm (all round the diameter of the pipe). This tube was wrapped in a single layer of nylon mesh (0.3 mm mesh) held in place with four cable ties (Figure 11). In the bottom of the water butt, a layer of gravel (12 mm gravel) was laid up to, and approximately 1 cm above, the perforated tube outflow (Figure 12). On top of this gravel layer, a layer of the test sand was placed to a depth of about 30 - 40 cm. Water was supplied to this simple filter arrangement via a ½ inch bore ball cock valve which was placed through the side near the top of

Figure 5: General view of the two SSF test rigs on location at a commercial nursery. (A) is the sand comparison rig and (B) is the barrel-type pilot rig.



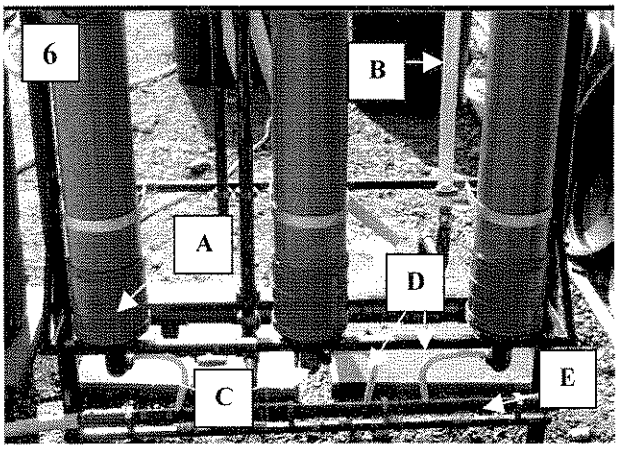
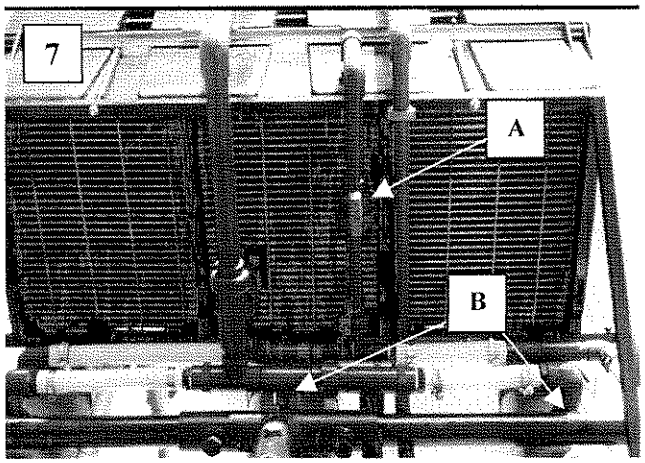


Figure 6: (A) Cap fitting; (B) Head loss manometer tube; (C) ¼ Inch needle valves; (D) Tricoflex tubing connectors for sample collection; (E) Drainage tube.

Figure 7: View of the base of the header tank at the top of the frame of the sand comparison rig. (A) Valve regulating water flow into columns; (B) Column overflows, maintaining constant water head.



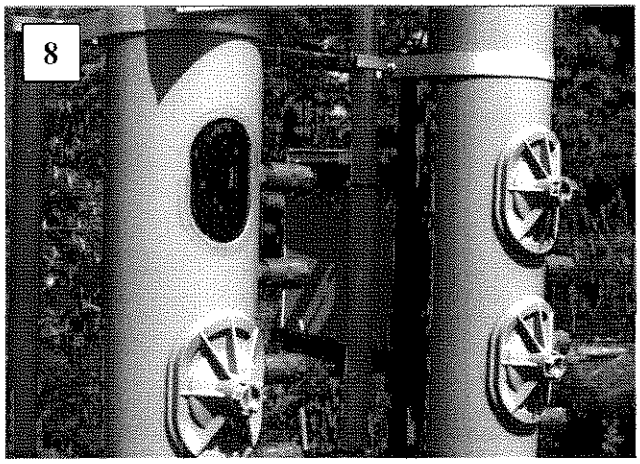


Figure 8: Close-up illustration of hatches on column fronts, one of which is removed to show the size of the access aperture.

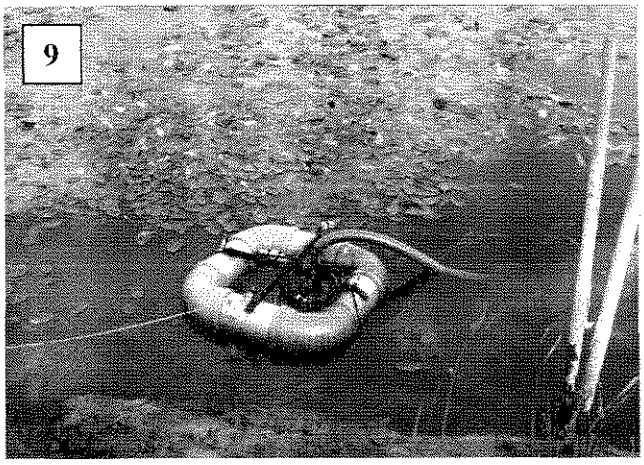


Figure 9: Raft for suspending the submersible pump in the reservoir at Nursery C.

Figure 10: General view of barrel-type pilot SSF. (A) shows position of exit tap and (B) shows position of raw water feed to ballcock.

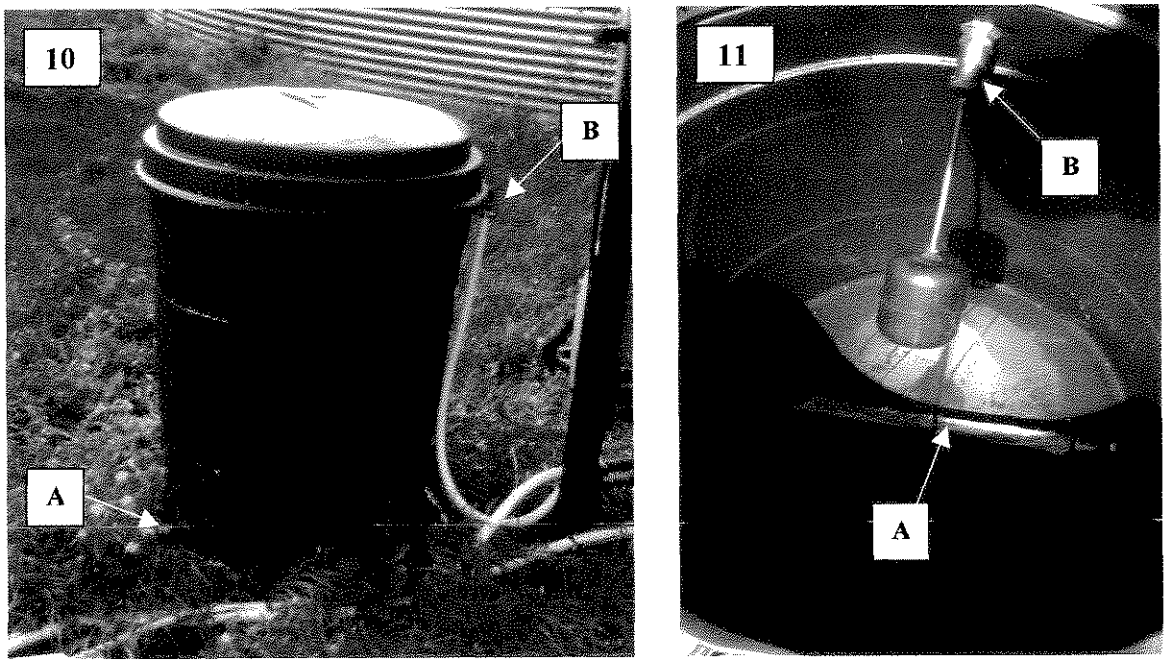


Figure 11: Inside of barrel-type pilot SSF, showing (A) the drainage tube attached to the inside of the tap fitting and (B) the position of the ballcock valve.

Figure 12: Illustration of the gravel drainage layer (A) inside the pilot filter, showing how the sand layer is simply placed directly on top of the gravel (B).

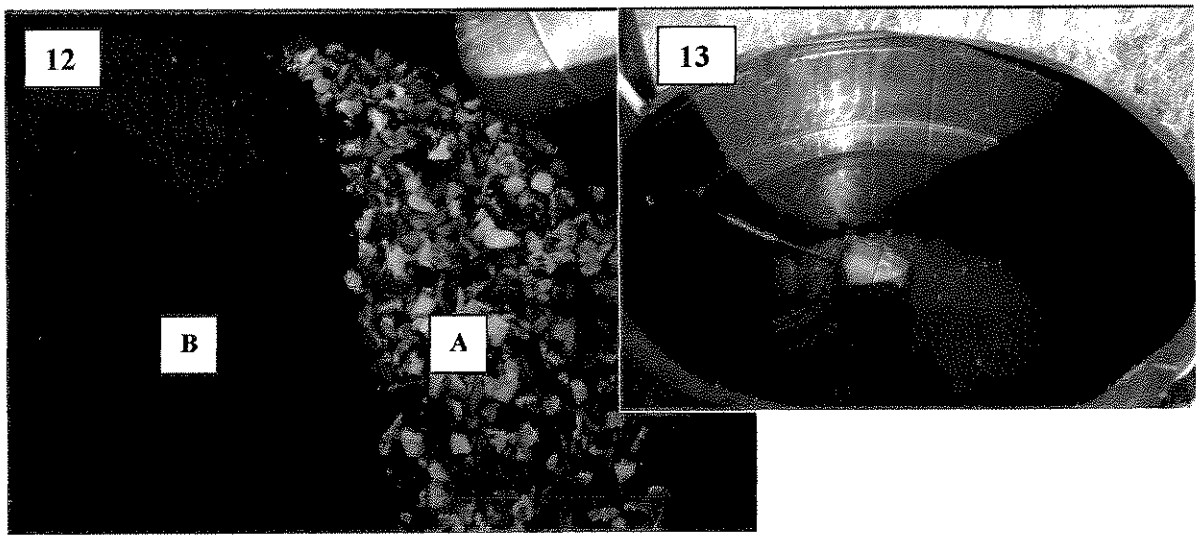


Figure 13: Operational barrel-type pilot SSF, showing maintenance of constant water head over the sand using a ballcock valve.

the barrel and arranged to give a water level that provided a water head of at least 40 cm above the sand (Figure 13). In the experimental systems described here, untreated water was supplied to the ballcock valves via gravity flow from the header tank of the sand comparison rig. (However, any system of supplying water to the valve would be suitable.) The surface area of the filter sand was calculated by πr^2 and the volume of water expected per hour was calculated using $\pi r^2 h$, where h is the filter flow rate in mh^{-1} (which should be between 0.1 and 0.2 mh^{-1}). The pilot filter's flow rate could then be easily set by adjusting the water butt tap to supply the calculated correct volume of water in 30 seconds.

At all sites except the one using river water, treated water draining from both the test rigs was collected, via drainage pipes, in a 114 l black polythene tank. A pump (Nova 200 submersible), controlled by float switch, was suspended in the tank using steel Bowden cables attached to the lid which was constructed from 18 mm sterling board. Treated water was pumped from this tank back to the reservoir source via 18 mm 'Tricoflex' polyester cord-reinforced pvc water hose.

Installation of SSF rigs

At each of the four sites outlined above, a combination of one pilot filter and one sand comparison rig (3 columns mounted on a steel frame) were installed. The pilot filter barrel was simply placed on a 60 x 60 cm paving slab which had been laid and levelled on a small (3cm thick) bed of builders' sand. The location and positioning of the test rigs was decided on an initial visit to each site, as were the arrangements for collecting water described above.

The heavy steel frame of the comparison rig was designed with legs with detachable end sections which would slide into 1 m depth locating sockets embedded and firmly held in a prepared concrete foundation. Holes were dug and the two 2 inch medium grade ("blue") BSP tubular locating sockets positioned and concreted-in on the first site visit, using a specially prepared jig. Sockets were arranged with their tops level to one another and approximately at ground level.

The detachable leg extensions for each frame leg consisted of 70 cm lengths of 1½ inch heavy grade ("red") BSP pipe. Around one end of each leg extension, a 40 mm collar of 2 inch medium grade BSP pipe was welded which held in place a square flanged collar containing four 18 mm bolt holes and a central 36 mm locating hole. Into the base of each leg of the frame, a 20 cm length of 1 inch heavy grade BSP pipe was inserted and welded into position with 5 cm protruding from the end to form a location spigot. In addition, a similar 40 mm collar and square flange to those attached to the leg extensions was welded onto the end of each leg.

At installation, the leg extensions were inserted into the foundation sockets. The frame was manoeuvred into position so that the 'male' spigot ends of the frame feet fitted into the 'female' tops of the leg extensions, and the frame was secured in position by bolting the matching square flanges together. Additional support for the frame was provided using an angled backstay which was attached close to the top of the frame. This was taken off at an angle of 35° and bolted to a

leg previously secured with a 1 m peg running through it at 90° and held in place with concrete.

Sands: selection and measurement

Sands for comparison in the test rigs were obtained from seven locations (Table 1). The majority of the sands obtained were described as 'fine washed'. In addition to these, some sands were adjusted in composition by sieving. This was done both to produce a sand which matched 'ideal' characteristics described in the water industry literature and to produce some sands which were much coarser than would normally be considered suitable for SSF.

Samples of 1 kg of each sand tested were dried and their grain size distributions were determined by sieve analysis. When the cumulative weight of sand is plotted against sieve mesh diameter, it provides much information about the sand. However, these curves provide two simple parameters of sand grain size distribution which are regularly used by the water industry to judge the suitability of sands for SSF use. These are the effective size (ES_{10}) and the uniformity coefficient (UC).

The ES_{10} of a sand is the sieve mesh size through which 10% by weight of the sand will pass.

Sand with a high degree of uniformity is desirable for SSF and the UC gives a measure of this. The UC is calculated by dividing the sieve mesh size through which 60% by weight of the sand passes (ES_{60}) by the ES_{10} of the sand. If there are large amounts of fine or coarse grains in a sand, this will affect the values of the ES_{10} and ES_{60} and will therefore influence the UC value.

For drinking water production using SSF, recommendations for ES_{10} vary greatly, although generally a value of about 0.2 – 0.25 mm is considered optimal. A low UC is considered desirable and the UC should always be below 3.0 and preferably less than 2.0 (Van Dijk & Oomen, 1978).

Water Sampling and Analysis

As in previous studies (HDC HNS 88), the bulk of the monitoring work carried out in this project consisted of collection and microbiological analysis of water samples. Water samples were collected in sterile bottles (autoclaved 1 litre Nalgene polypropylene bottles). The minimum sample size collected was 1 litre and all samples were processed and plated within 24 h of collection. Whenever SSF effluent samples were collected, a raw water sample was also collected as a standard. For convenience in sampling, these two samples were collected at the same time without taking the filter retention time into account. This was justified by observations in MAFF-funded work indicating that the retention time would range between <1 and 3 hours, over which time the quality of a large supernatant water volume would not drastically alter.

Table 1 **Outline descriptions of the 12 sands used in this study, giving reference number, region of origin, brief description and parameters of grain size distribution**

Sand No.	Area of source quarry	Brief description of sand	ES_{10}	ES_{60}	UC
1	SW Hampshire	Sand 8 sieved to prepare 'ideal' sand	0.30	0.56	1.87
2	SE Worcestershire & S Hampshire	Mixture of Sand 8 and Sand 3	0.23	0.51	2.21
3	SE Worcestershire	Sand used for sand beds	0.31	0.49	1.58
4	N Worcestershire	Sand 5 sieved to increase its coarseness	0.33	0.92	2.78
5	N Worcestershire	Sand used for sand beds	0.22	0.43	1.95
6	N Norfolk	Sand 7 sieved to increase its coarseness	0.30	1.24	4.13
7	N Norfolk	'Lime-free sharp sand' used for sand beds	0.21	0.80	3.81
8	SW Hampshire	'70/30 5/2 mm plasterer's mix'	0.23	0.50	2.17
9	SW Hampshire	'5 mm sharp sand'	0.29	1.07	3.69
10	W Devon	'Fine sand' (China clay bi-product)	0.20	0.49	2.45
11	S Essex	'Sharp sand'	0.31	0.48	1.55
12	NE Hampshire	'Fine sand' used for sand beds	0.30	0.83	2.77

ES_{10} is the estimated size of the sand and is the sieve mesh diameter through which 10% by weight of the sand will pass.

ES_{60} is the sieve mesh diameter through which 60% by weight of the sand will pass.

UC is the uniformity coefficient of the sand and is calculated by ES_{60}/ES_{10}. The lower the UC value, the more uniform the sand is.

On arrival in the laboratory, water samples were measured for pH and EC and divided into two portions: 750 ml for plating, following concentration by membrane filtration, and the remainder (usually 250 ml or more) for bait assay.

Samples for membrane filtration were passed under vacuum through 47 mm diameter, 3.0 µm cellulose nitrate membrane filters housed in autoclaved Nalgene reusable membrane filtration funnels. Membrane filters were cut into approximately 1 cm squares and placed in sterile glass universal bottles containing 5 ml of a re-suspension medium (0.1% w/v aqueous agar) and shaken for 5 minutes at 500 rpm of a flask shaker (Stuart). Aliquots (0.5 ml) of the resulting suspensions were plated out on PDA, *Fusarium*-'selective' agar (Pettitt, Parry & Polley, 1993) and on Phycomycete-selective agar (modified BNPRA – Pettitt & Pegg, 1991). All plates were incubated at 20°C for 48 h and counts (cfu l^{-1}) were made of the following fungus species: *Fusarium* Spp., *Trichoderma* spp., total Phycomycete, *Pythium* spp., and *Phytophthora* spp.

Bait tests were also carried out with surface sterilised *Rhododendron* leaf disks using the method described by Pettitt *et al.* (1998). The water samples were retained in their original sample bottles, to which 10 leaf disks were added. After 24 h incubation at 20°C, leaf disks were collected in sterile sieves, blotted dry, on autoclaved tissue paper, and plated onto BNPRA. After a further 36 h incubation, the percentage of baits infected was determined.

Experimental Programme

The columns on the sand comparison rig at Efford were emptied and re-sanded after filtration runs in order to compare a larger number of sands. On the other three sites, the three sands of choice were compared throughout the trial. In every filtration run, two different sands were compared with an 'ideal' sand prepared by sieving a sand obtained locally at Efford and already extensively (and successfully) used in SSF experiments. Once sieved, this sand had an ES_{10} of 0.30 mm and a UC of 1.87. Each of the 4 barrel-type pilot test rigs was filled with a locally-sourced sand.

Initially all filters were run at a flow rate of 0.1 mh^{-1}. Filters were monitored by water sampling, as outlined above, as frequently as possible, until mature (maturity was defined as the stage at which all fungal propagules were removed from the filtrate). All filters were then run for a period of 2 months, or longer, over which time the development of head loss was monitored by manometric measurements using the transparent manometer tube described above.

After the initial run period, the flow rate on all filters was increased to 0.2 mh^{-1} and left to stabilise for 2 or more weeks before efficacy was monitored. If necessary, prior to increasing the flow rate, filters were cleaned by scraping (see HDC HNS 88) and reprimed. Once the efficacy of the test filters, at a flow rate of 0.2 mh^{-1}, had been established, the procedure was repeated, increasing the filtration flow rate to 0.3 mh^{-1}.

Results And Discussion

Sands

The grain size characteristics of the sands assessed in this study are outlined using the terms ES_{10}, ES_{60} and UC in Table 1. The sources of sands are only given by region, as this Table is not intended to be prescriptive in terms of sand suppliers. Indeed, the aim of this project has been to demonstrate the wide availability of sands suitable for SSF. A 'sharp' sand was obtained by each of the nurseries where SSF rigs were tested. In each case, this was a sand frequently used for the creation of sand beds on which to stand nursery stock.

A second sand for comparison on each site was prepared by removing a proportion of the finer fractions using a 250 μm sieve. Brief descriptions of these sands are also given in Table 1.

Sieving out the fine fraction produced sands with higher ES_{10} values (sands 4 and 6, Table 1), but also increased the influence of the coarser fractions on the ES_{60} value, with the effect of increasing the UC. This increase in UC was avoided when preparing the third 'ideal' control Sand 1, by sieving out grains larger than 1.5 mm in addition to sieving out the fine fraction.

Progress of filtration runs on each nursery

Installation of the SSF test rigs took varying amounts of time, depending on the local problems associated with each site.

Nursery A was actually the second site to receive SSF apparatus, but it was the most straightforward (apart from HRI Efford!) to install. At this site, rainwater, mainly from twinspan polythene roofs, was collected in a 20,000 gal (91 m^3) tank. This water contained large populations of Phycomycete water moulds and sporadically high (50-60 cfu l^{-1}) populations of *Pythium* spp. The SSF rig was located next to this tank, extracting untreated and returning treated water directly to it. The untreated water was of very low turbidity and a filtration run of 188 days was completed (the filter was started in June 1999 and is still running now in March 2000), with 3 flow rates, without the need for a clean up. One problem was caused with the operation of the flow of the comparison column containing Sand 1, which was found to be blocked by a small bird which became trapped in the top of the column on day 36 of the filter run. To avoid a repeat of this or similar events, small wire mesh covers were placed internally at the top of all comparison rig columns. Sand 1 was fully primed at Nursery A after 13 days (Tables 2 + 3). The remaining sands matured at different rates, but were all primed by 54 days. Comparisons of efficacy will be dealt with in a later section.

At Nursery B, the main problem was the large variation in the depth of the small river from which water was being abstracted. The height of lift from the river when it was low was too much for the first pump used. Ideally, this problem should have been dealt with by using this pump to deliver water to a settling tank at the base of the filter rig, and a second pump to deliver

water to the header tank. However, the complexity of wiring this option off site and the time restrictions, led us to solve the 'lift' problem by using a larger pump to supply the header tank directly from the river. This ultimately led to the second problem encountered at this site of periodically high levels of suspended fines in the river water being delivered directly to the SSF rig. This material caused two blockages of the filters during the SSF run and it was necessary to clean the filters by scraping (see HDC HNS 88) between experimental changes in filtration flow rate (see Table 4). Although a problem from the operational view, these large increases in head loss (Figure 14b) caused by suspended fines were interesting experimentally and may have helped to expose differences in the sands being compared. Filter priming was reasonably fast at Nursery B, with all filters effective against Phycomycetes after 29 days, and against *Trichoderma* and *Fusarium* after 37 days (Tables 4 + 5).

Nursery C was left until last because of a problem with positioning the SSF test rig in relation to the water and electrical power supplies. This was finally solved using a long boom to cross the wide reservoir berm at this site, as described in 'Materials and Methods' above, allowing the rig to be located near to the power supply. Once installed, this rig ran well and all sands compared were fully primed [Table 6 (i) and (ii)]. However, due to circumstances at the nursery, this filtration run had to be curtailed at 65 days.

Filtration runs were not started at HRI Efford until August 1999, but were reasonably 'trouble free'. A total of six sands were compared in two runs using the comparison rig alone. The two filtration runs lasted for 66 and 62 days and all sands were observed as fully primed after 35 and 28 days respectively [Table 7 (i) and (ii)]. The rate of increase in head loss was considerably higher in the first run than the second and it was necessary to scrape the filters clean before increasing the flow rate from 0.2 to 0.3 mh^{-1} on day 35 (Table 7 and Figure 15a & b). The head loss increase seen at the HRI Efford site was caused by algae in the pond. These algae appear to have a greater effect on the flow through small experimental filter columns than on larger filters, and this was observed at Efford, where non-experimental runs with barrel-type filters operating in parallel with the first run did not appear to have severe blockage problems.

Sampling procedures

Progress of SSF runs was monitored by collection and analysis of water samples as frequently as reasonably possible. On each site visit, raw water was collected from the rig header tank (and from the source for comparison) and treated water was collected from each column and the barrel pilot filter. After sample collection, the head loss of each column on the sand comparison rig was determined.

In experimental work carried out on SSF at HRI Efford, use was made of artificial inoculations with plant pathogen spores. However, with comparisons of filter efficacy carried out on commercial nurseries, such inoculations were not possible. This was not a problem, as use was made of naturally occurring populations of fungi. *Fusarium* spp. (predominantly *F. oxysporum*)

were present in all raw water samples except at Nursery A on 12.1.00. Similarly, *Trichoderma* spp. were present in all raw water samples except at Nursery A on 8.7.99. Naturally occurring Phycomycetes were particularly useful, especially members of the almost 'ever present' Saprolegniacae. *Pythium* spp. (some pathogenic) were also abundant and frequently encountered at all the nurseries with SSF rigs. The presence of zoospores of any phycomycete species in a sample of treated water from a SSF, regardless of whether or not it is a phytopathogen, is a good indication of poor efficacy and a risk of penetration by aggressive pathogens such as *Phytophthora* spp.

Since natural populations of fungal species fluctuate over time, sand filter efficacy was determined by percentage removals of selected fungus species (Tables 2-6). At the three commercial nurseries, fluctuating populations of *Fusarium* spp., *Trichoderma* spp. and Phycomycetes in raw water were broadly comparable, with cfu concentration ranges of *Fusarium* spp. of 20 to 233 cfu l^{-1}, of *Trichoderma* spp of 13 to 110 cfu l^{-1}, and Phycomycetes 16 to 348 cfu l^{-1}. Although controlled inoculations with *F. oxysporum* and *Phytophthora cryptogea* were used at HRI Efford, the data from these experiments is presented in the same way to allow comparisons to be made between sites and sample dates.

pH and electroconductivity

From the observations in this study, neither water pH over the range 6.6 – 8.8, nor electro-conductivity (EC) over the range 0.09 – 1.22, affected the efficacy of SSF activity against plant pathogens.

Conversely, SSF did not have a significant effect on either the pH or the EC of the treated water either. Changes, if they occurred at all, were slight, and there were no trends towards increases or decreases in pH or EC as a result of SSF treatment of the water.

The range of pH over which effective SSF activity was observed was 6.6 – 8.8 (Table 8), with the most variation in pH at Nursery C.

The highest EC values were consistently observed at Nursery B. This was due to the high natural salt content of the river source for raw water at this site. EC values were lowest for Nursery A and HRI Efford, where the majority of the raw water was rainwater. Slightly higher EC values were observed at Nursery C. This is probably the result of nursery runoff water which was a small component of the raw water treated on this site.

Sand efficacy comparisons

All twelve sands compared in this study were effective at removal of Phycomycetes, *Fusarium* spp. and *Trichoderma* spp. once finally primed at filtration flow rates of 0.1 mh^{-1} and 0.2 mh^{-1}. All sands were more effective at removing Phycomycete propagules than those of *Fusarium* spp.

and *Trichoderma* spp. The conidia of *Trichoderma* spp. and the micro conidia of *F. oxysporum* are almost one tenth the size of the average Phycomycete zoospore, and this may account for these propagules' ability to penetrate SSF until later in the filter maturation period.

Once fully mature, a SSF can be reasonably expected to remove all propagules of the above-mentioned groups Indeed, the best fully mature filters will remove all fungal propagules. The sensitivity of efficacy against *Trichoderma* spp. and *Fusarium* spp. makes these groups useful markers for the effects of elements such as sand quality and filtration flow rate on SSF efficacy.

In all filtration runs, increases in the filtration flow rate initially disturbed SSF efficacy (Tables 2-7), and a period of 'settlement' was necessary until full efficacy was restored. This shows that increases in filtration flow rate during the commercial operation of SSF carry a great risk of pathogen penetration and should be avoided, unless the filter can be switched to recirculate to the untreated source until properly settled to the new flow rate (a process that would need to be monitored by water testing). When the filtration flow rate was increased from 0.2 to 0.3 mh^{-1}, there was some indication of a breakdown in SSF efficacy with a number of sands, even after a settlement period of more than 30 days.

Sands 3, 4, 5, 9, 11 and 12 showed signs of loss of efficacy at the higher flow rate, largely as indicated by diminished removal percentages of *Fusarium* spp. and *Trichoderma* spp. In addition, Sands 4 and 5 also lost efficacy against Phycomycetes at Nursery B. These sands were not compared on other sites and their poor performance at 0.3 mh^{-1} might be in part due to the problems of blockage and high rates of head loss (Figure 14) seen at Nursery B in the absence of prefiltration treatmentsIn addition the poorer performance of these two sands may be linked to the coarse fraction (particles 1.5 mm), which had been sieved from Sand 1 but was present at 22.3% and 18.5% of total in Sands 4 and 5 respectively. However, these sands were compared with the project standard, Sand 1, which performed well under the same conditions (Tables 4 + 5).

At higher flow rates, the presence of these larger grains may have caused a minor amount of channelling to occur, allowing fungus propagules to bypass some of the filter column and a small percentage to pass through the entire filter column.

Barrel-type pilot test filters

The barrel-type test rigs were very simple devices which worked well on all test sites. Unlike the sand comparison rigs, installation of these filter rigs was not problematic. Assembly and operation were easily achieved and produced reliable results on potential performance of sands in SSF.

The aim of this pilot rig was to provide a small simple test system to demonstrate SSF efficacy on location. The rig was designed for economy and the water barrels used in the present study

were at the lower height limit for a SSF test rig, as they allowed for only a 10 cm gravel drainage layer, 35-45 cm of sand and 40-60 cm of water head. A sand depth of 35-45 is at the minimum end of the scale for SSF efficacy and this was demonstrated by results in Tables 2-7. The barrel-type filters worked consistently well at flow rates up to 0.2 mh^{-1}. However, these filters were the most likely to breakdown with increasing filtration flow rate as a result of their smaller depth of sand, since, as the flow rate increases, so does the minimum depth of sand needed for SSF to remain effective.

Identification of the minimum effective depth for a given sand at a given flow rate on the particular site in question is of key importance in deciding (a) whether the sand is good enough to use for SSF and (b) deciding on the size of sand filter that is required. This is because the sand filter size is determined by two factors; estimated water daily demand and estimated filtration flow rate. The filter surface area needed can be calculated by a simple formula:

$((a + b) \div 24) \div c$ = filter surface area

where: a = maximum daily water demand (m^3); b = daily safety margin "volume of under (m^3) and c = filtration flow rate (determined using pilot rig mh^{-1}).

In addition to the simple question of SSF efficacy, the development of filter blockages was readily assessed using the barrel pilot rig. The larger surface area barrel filters appeared able to continue filtering at higher levels of head loss than the comparatively narrow sand comparison rig columns.

Samples of material clogging the sand surface were also readily sampled. This will be useful in determining the type of pre-filtration best suited to an individual site, as the particle type and size distributions can be identified from such samples. Similar test rigs will be used in HDC-funded project HNS 88b, which will study pre-filtration treatments and cleaning treatments in order to reduce the number of filter blockages and speed up the filter cleaning operation.

Figure 14 (a): Development of head loss at Nursery A

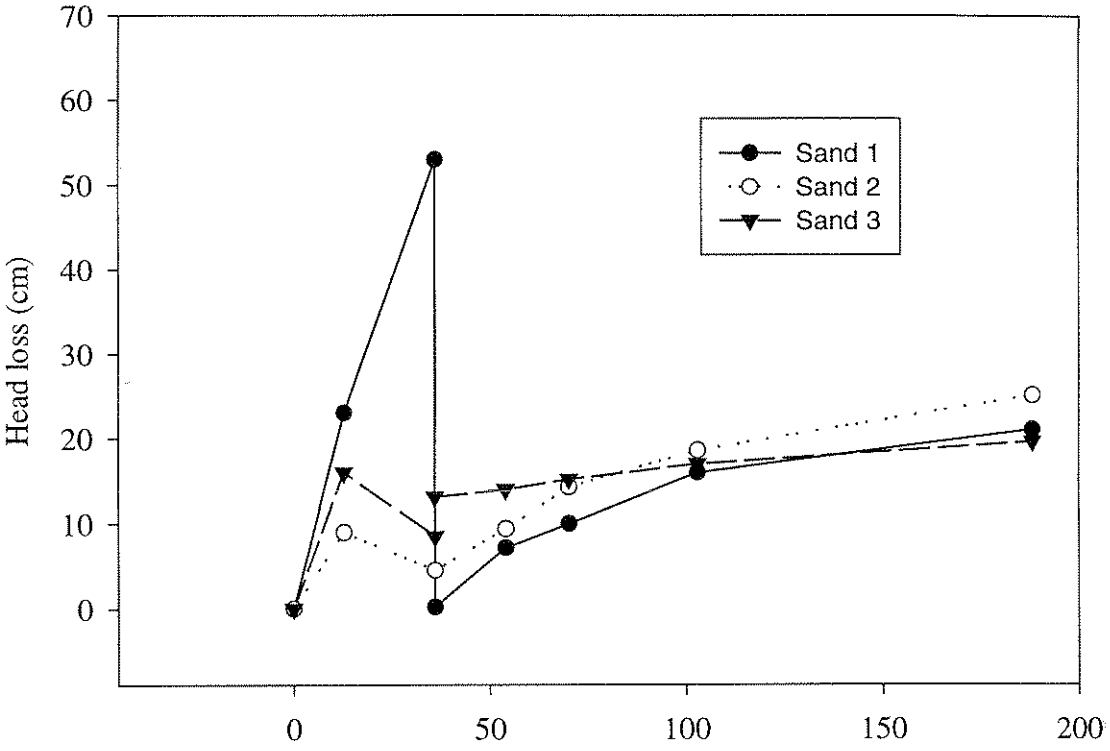


Figure 14 (b): Development of head loss at Nursery B

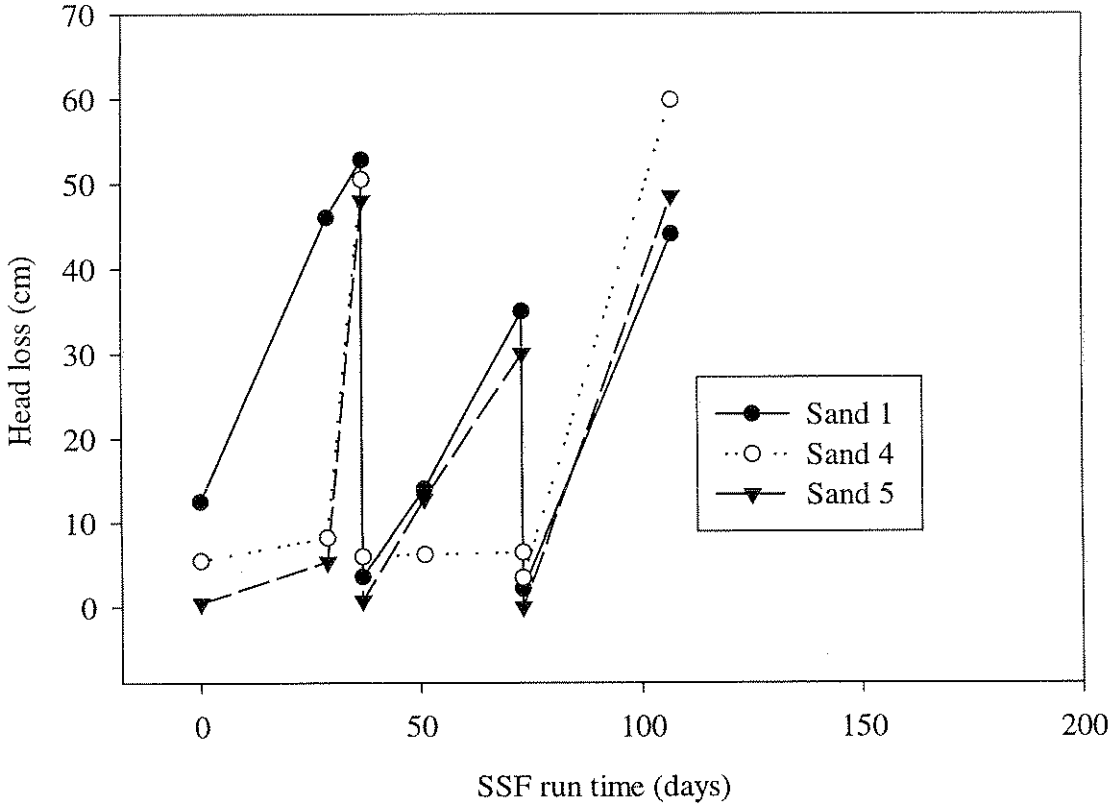


Figure 15 (a): Development of headloss during SSF run 1 at Efford

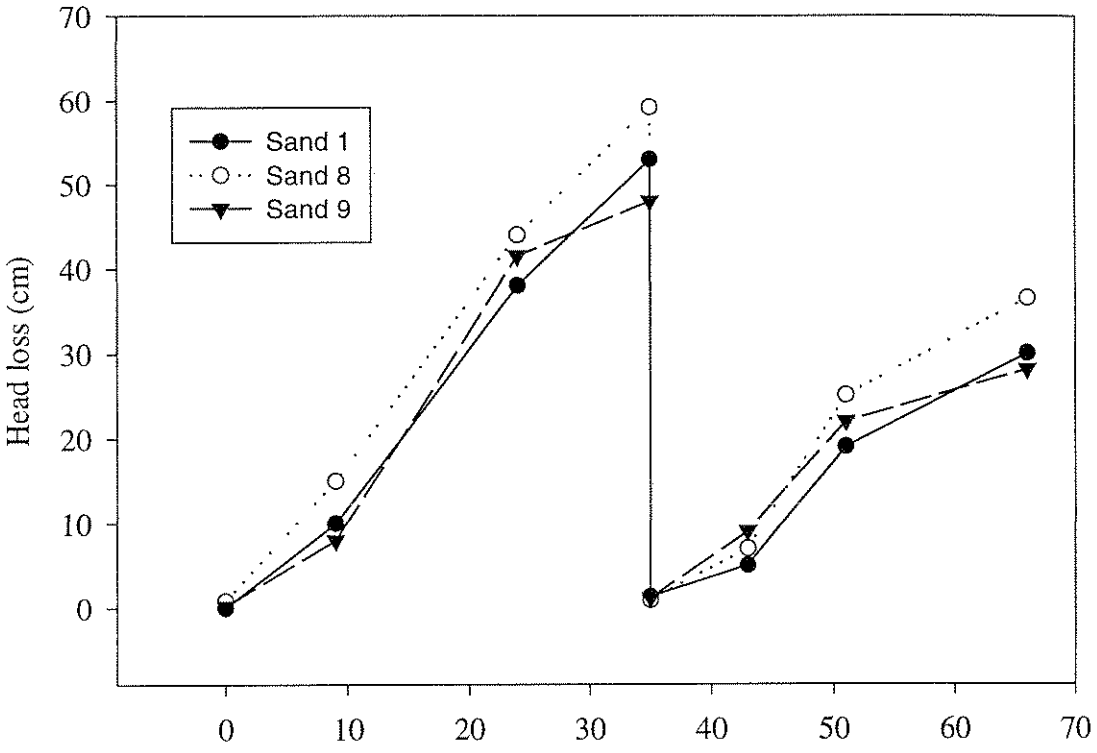


Figure 15 (b): Development of headloss during SSF run 2 at Efford

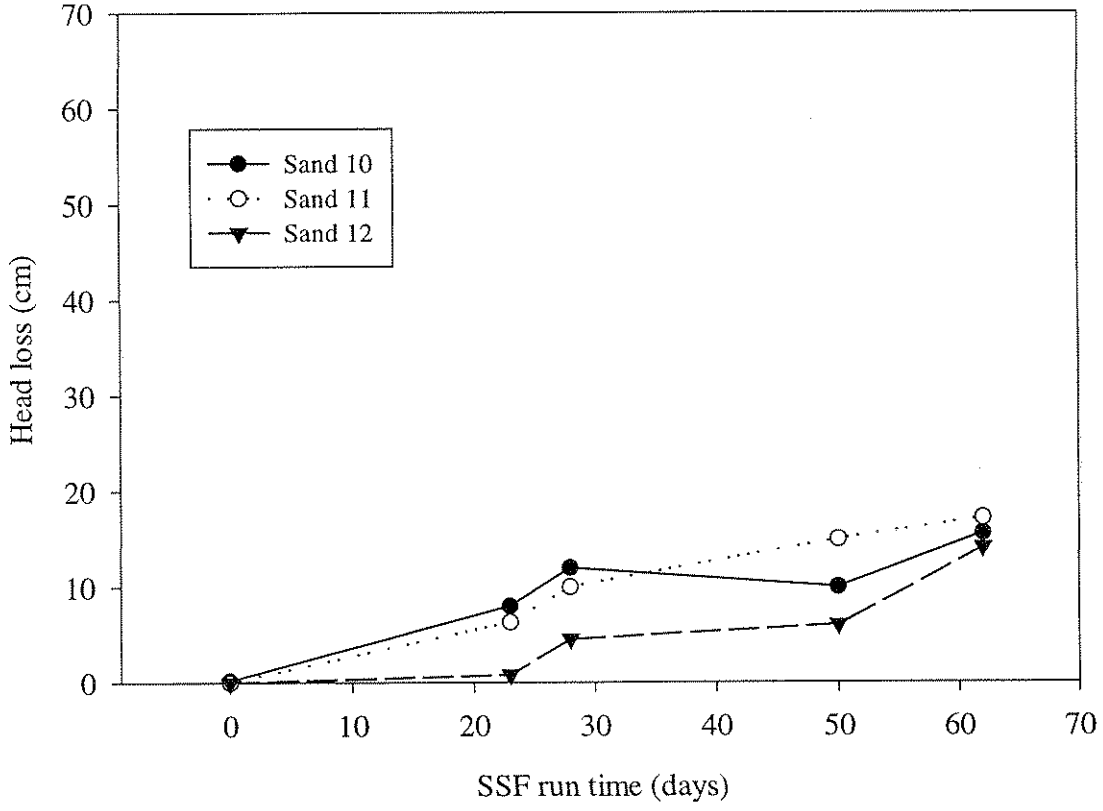


Table 2 **Comparisons of the efficacy, as determined by % removals of Phycomycetes (as indicated by bait tests and plate tests), of filter sands and a barrel-type pilot test rig at different flow rates at Nursery A**

Date	t (days)	Filtration flow rate (mh^{-1})	Sand (1)		Sand (2)		Sand (3)		Pilot (Sand 3)	
			Baits	cfu[a]	Baits	cfu[a]	Baits	cfu[a]	Baits	cfu[a]
8/7/99	0	0.1	0	0[b]	10	23	0[b]	0	0	30
21/7/99	13	0.1	100	100	20	6	0	86.6	90	91.7
13/8/99	36	0.1	100	99.6[c]	38	75.5	50	95	100	100
31/8/99	54	0.1→0.2[d]	100	100	100	100	100	100	100	100
16/9/99	70	0.2	100	100	100	100	100	100	100	100
19/10/99	103	0.2→0.3[d]	100	100	100	100	100	100	100	100
12/1/00	188	0.3	100	100	100	100	100	100	100	100

[a] cfu = colony forming units

[b] Filtered sample contained more cfu[a] than raw water sample

[c] A dead fledgling bird was found in the top of the filter column on this date

[d] Filter cleaning and repriming was not necessary before moving on to the next flow rate

Table 3 **Comparisons of the efficacy, as determined by % removals of *Trichoderma* spp. and *Fusarium* spp. of 3 filter sands and a barrel-type pilot test rig at different filtration flow rates at Nursery A**

t (days)	Filtration Flow rate (mh^{-1})	% removal by SSF							
		Sand (1)		Sand (2)		Sand (3)		Pilot (Sand 3)	
		Trichoderma (cfu[b])	*Fusarium* (cfu[b])	*Trichoderma* (cfu[b])	*Fusarium* (cfu[b])	*Trichoderma* (cfu[b])	*Fusarium* (cfu[b])	*Trichoderma* (cfu[b])	*Fusarium* (cfu[b])
0	0.1	-	100	-	100	-	0[c]	-	0[c]
13	0.1	100	100	0100	100	44	63	91.3	0[c]
36	0.1	100	75.5	100	86.8	51.9	62.3	100	86.8
54	0.1→0.2	100	100	100	100	100	100	100	100
70	0.2	100	80.6	100	0	100	74.1	100	93.4
103	0.2→0.3	100	100	100	100	100	89.6	100	100
188	0.3	100	-	100	-	60.6	-	85.1	-

a For dates see Table a

b cfu = colony forming units

c Filtered sample contained more cfu[b] than raw water sample

Table 4 **Comparison of the efficacy, as determined by % removals of Phycomycetes (as indicated by bait tests and plate tests) of 3 filter sands and a barrel-type pilot test rig at different filtration flow rates at Nursery B**

Date	t (days)	Filtration Flow rate (mh^{-1})	% Removals							
			Sand (1)		Sand (4)		Sand (5)		Pilot (Sand 5)	
			Bait	cfu[a]	Bait	cfu[a]	Bait	cfu[a]	Bait	cfu[a]
1/6/99	0	0.1	90	96.8	10	53.2	20	38.7	50	74.2
30/6/99	29	0.1	100	100	100	100	100	100	100	100
8/7/99	37	0.1→0.2[b]	100	100	100	92.5	0	25	100	100
22/7/99	51	0.2	70	92.5	100	85	40	91.5	60	98.5
13/8/99	73	0.2→0.3[c]	100	100	100	100	100	100	100	100
16/9/99	107	0.3	100	100	20	98	90	100	90	98

[a] cfu = colony forming unit

[b] Filter cleaning and repriming was necessary at the change to this flow rate on day 37

[c] Filter cleaning and repriming was not necessary before moving on to the next flow rate

Table 5 **Comparisons of the efficacy, as determined by % removals of *Trichoderma* spp. and Fusarium spp. of 3 filter sands and a barrel-type pilot test rig at different filtration flow rates at Nursery B**

		% Removal							
	Filtration	Sand (1)		Sand (4)		Sand (5)		Pilot (Sand 5)	
t (days)[a]	Flow rate (mh^{-1})	*Trichoderma* (*cfu*[b])	*Fusarium* (*cfu*[b])	*Trichoderma* (*cfu*[b])	*Fusarium* (*cfu*[b])	*Trichoderma* (*cfu*[b])	*Fusarium* (*cfu*[b])	*Trichoderma* (*cfu*[b])	*Fusarium* (*cfu*[b])
0	0.1	78.3	41.3	78.3	33.8	66.7	8.8	70	23.8
29	0.1	100	100	0[c]	0[c]	100	0[c]	67.5	100
37	0.1→0.2	100	100	100	100	100	100	100	100
51	0.2	100	60	90.9	66.6	100	66.6	100	0[c]
73	0.2→0.3	100	100	100	100	100	100	100	100
107	0.3	100	100	26	65	52	100	74	35

[a] For dates see Table d

[b] cfu = colony forming units

[c] Filtered sample contained more cfu[b] than raw water sample.

Table 6 (i) and (ii) **Comparison of the efficacy of 3 sands, as determined by % removal of Phycomycetes (i) and by % removal of *Trichoderma* spp. and *Fusarium* spp. (ii) at a single filtration flow rate (0.2 mh^{-1}) at Nursery C.**

(i) % Removal of Phycomycetes

Date	t (days)	Sand (1)		Sand (6)		Sand (7)		Pilot (Sand 7)	
		Baits	cfu	Baits	cfu	Baits	cfu	Baits	cfu
20/7/99	0	10	0	20	72.7	40	81.8	20	81.8
23/9/99	65	100	100	100	100	100	100	100	100

(ii) % Removal of *Trichoderma* spp. and *Fusarium* spp.

t (days)	Sand (1)		Sand (6)		Sand (7)		Pilot (Sand 7)	
	Trichoderma	*Fusarium*	*Trichoderma*	*Fusarium*	*Trichoderma*	*Fusarium*	*Trichoderma*	*Fusarium*
0	100	100	73.3	100	100	92.5	88.4	57.0
65	100	100	100	100	100	100	100	100

Table 7 Comparisons of the efficacy of filter sands at removing *Phytophthora cryptogea* zoospores and *Fusarium oxysporum* microconidia, at two filtration flow rates (0.2 and 0.3 mh-1) at HRI Efford

(i) Comparison between sands 1,8, and 9 and
(ii) Comparison between sands 10, 11, 12[a]

(i) % Removals by sands

t (days)	Filtration flow rate (mh^{-1})	Sand (1) *Phytophthora* (cfu)[b]	Sand (1) *Fusarium* (cfu)[b]	Sand (8) *Phytophthora* (cfu)[b]	Sand (8) *Fusarium* (cfu)[b]	Sand (9) *Phytophthora* (cfu)[b]	Sand (9) *Fusarium* (cfu)[b]
0	0.2	9	0[c]	12	1	3	0[c]
9	0.2	100	42	51	81	92	32
24	0.2	100	65	100	100	100	84
35	0.2→0.3[c]	100	100	100	100	100	100
43	0.3	100	84	100	86	92	88
51	0.3	100	100	100	99	99	97
66	0.3	100	100	100	100	100	96

(ii) % Removals by sands

t (days)	Filtration flow rate (mh^{-1})	Sand (10) *Phytophthora* (cfu)[b]	Sand (10) *Fusarium* (cfu)[b]	Sand (11) *Phytophthora* (cfu)[b]	Sand (11) *Fusarium* (cfu)[b]	Sand (12) *Phytophthora* (cfu)[b]	Sand (12) *Fusarium* (cfu)[b]
0	0.2	57	25	2	0[c]	12	17
23	0.2	99	10	99	80	94	77
28	0.2→0.3	100	100	100	100	100	100
50	0.3	100	91	98	60	96	34
62	0.3	100	100	100	82	100	90

[a] See Table 1 for details of sands assessed
[b] cfu = colony forming units
[c] high head loss necessitated scraping of filters before increasing the flow rate

Table 8 **Ranges of pH and electroconductivity observed at the four test sites over the period of SSF runs**

(No significant differences in pH and EC were observed between SSF-treated and raw water)

Nursery site	pH range	EC range (mS)
Nursery A	7.02 – 8.35	0.13 – 0.64
Nursery B	7.09 – 7.95	0.75 – 1.22
Nursery C	6.60 – 8.80	0.55 – 0.85
HRI Efford	6.92 – 7.87	0.09 – 0.38

CONCLUSIONS

1. Sands from a wide range of sources worked well in SSF at filtration flow rates up to 0.2 mh-1.

2. The types of sand that appear to be appropriate are lime-free sharp sands such as sands suitable for use in Efford-type sand beds.

3. Avoid sands with a coarse fraction (i.e. >1.5 mm grains) greater than 8-10% of total sand weight.

4. At a filtration flow rate of $0.3mh^{-1}$, only 'top quality' (i.e. ES_{10} 0.2 – 0.3 UC>2 and ES_{90}<1.5 mm) sands appear to maintain full efficacy (i.e. control of *Fusarium* spp., *Trichoderma* spp. and Phycomycetes).

5. Small-scale pilot filters constructed using 330 litre water butts worked well on all 3 commercial nursery sites assessed, providing useful practical information for the tailoring of SSF designs to particular sites. Information provided by running these simple systems included:

   - flow rate possible for sand under test at the site
   - potential for filter blockages occurring
   - nature of particles causing blockages (if they occur), thereby helping identify the type of pre-filtration system suitable.

6. Microbiological testing of water is important if these types of systems are to be adopted. It is wise to consider regular testing of any water supply that is derived from surface or rain runoff sources.

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