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Contaminated Land Remediation:

A Review of Biological Technology

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Department of Trade and Industry

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Biotechnology at work

BIO-WISE is a major UK Government Programme funded by the Department of Trade and Industry. It aims to:

- Improve the competitiveness of UK industry
- Support the development of the UK biotechnology supply industry.

Contaminated Land Remediation: A Review of Biological Technology

This review has been produced by the BIO-WISE Programme with the assistance of Richard Swannell of AEA Technology plc.

This is one of a series of reviews covering environmental biotechnology. Other reviews in the series are:

- Anaerobic digestion
- Biosensors
- Solid waste treatment
- Volatile organic compound (VOC) and odour abatement

For copies of these reviews, please contact the BIO-WISE Helpline on 0800 432100.

How can bioremediation help your company?

Decades of industrial activities such as mineral extraction, smelting, oil refining, engineering and gas manufacturing have left many sites in the UK contaminated with oils, solvents, metals and other pollutants. Leaks, spills and disposal practices at factories, warehouses, laboratories, garages, farms, workshops, storage depots and military bases have all added to the problem of contaminated land in the UK. It is estimated that the area affected by contamination in the UK may be as much as 360,000 hectares.

Economic growth in the UK is driving property developers to find new sites. Restrictions on building on greenfield sites and initiatives promoting the redevelopment of brownfield sites are encouraging developers to consider areas with varying degrees of contamination. Many of these areas are in prime urban locations, where treated land will have a high value. The new statutory powers of regulators and local authorities to inspect potentially contaminated sites and to serve owners with remediation notices have focused boardroom attention on the requirement to treat contaminated land. Site owners need to be aware that:

- planning conditions can require a site investigation to assess the quality of the land and to ensure it is fit for its intended use
- they may be at risk of legal action if they cause contamination to a neighbouring site or release contamination that poses a hazard to human health, natural ecosystems or controlled water
- they may be liable if the original polluter cannot be found.

Containment, and excavation and disposal have been the most commonly used technologies for the treatment of contaminated land. However, the increasing costs of long-term monitoring, excavation, transport, replacement soil and landfill disposal are encouraging the use of alternative methods of cleaning up contaminated land. Increasingly, bioremediation is being used as a cost-effective and sustainable option.

If you think bioremediation could benefit your company, then contact the BIO-WISE Helpline on freephone 0800 432100 for help in making an informed decision about whether bioremediation is the right option for your needs.

The Helpline can send you supplier details, put you in contact with a BIO-WISE Industrial Biotechnology Specialist and provide you with further free information. It can also signpost you to sources of advice on legislation governing contaminated land.

The requirement to remediate contaminated land should be evaluated on a site-specific basis within a risk management framework. Bioremediation technologies provide a number of advantageous tools for managing the identified risks.

The aim of this review

To help decide whether bioremediation can solve your contaminated land problem, you need to know what the technology involves and its current status in the UK. This review aims to show the potential benefits of bioremediation and to help UK companies understand:

- the need for remediation (pages 2 - 6)
- how bioremediation works (pages 6 - 8)
- the various bioremediation technologies available (pages 8 - 16).

A glossary is provided on page 19.

Site assessment using a risk management approach

In remediating contaminated land, the nature of contamination, the associated risks and selection of appropriate treatment technologies will be highly site-specific.

Companies are increasingly applying a risk-management approach, based on the potential effect on human health and the environment, to establish, and agree with the regulatory bodies a conceptual model for the migration of contamination on site. The risk management approach also enables the significance of contamination, the risks present and the required level (if any) of remediation to be established.

Risk assessment defines:

- the problem itself
- the size of the problem
- the potential consequences of the problem.

Such an assessment requires knowledge of the site, the environmental behaviour and toxicity of the chemicals present and the location of potential receptors (eg groundwater, rivers, human habitation or sensitive ecosystems). Developing a conceptual site model as part of the risk-based approach identifies the sources of contamination, any pathways of migration and potential sensitive receptors which may be affected.

The use of risk assessment methodology for contaminated land is outlined in the following paragraphs. A first step is to conduct a desk-based, site-history review. Information is gathered on:

- potential sources of contamination
- site history (eg details of any industrial activity on the site)
- obvious evidence of contamination (eg areas of dying vegetation)
- stained soil or deposits of contaminants
- details of local land use
- proximity to sensitive receptors.

If this initial review shows there is potential contamination on the site, then a site investigation is normally commissioned to determine the location and concentration of the contaminant or contaminants. With the information from the site investigation and historical review, pathways to sensitive receptors may be identified. Using this information, the levels of exposure of receptors to contamination can be estimated. This information can then be compared with toxicological data to evaluate the possible effects of the contaminants on receptors and the likelihood of these effects occurring. The data can be compared with guideline values which have been derived from conservative indicators of the toxicity of contaminants (such as those for chronic human exposure). Guideline values are for screening purposes and are not remediation targets. If the initial risk assessment suggests that sensitive receptors may be affected, then a more detailed assessment is recommended to measure transport and natural attenuation processes and compare the results with more detailed toxicological data. Alternatively, the risk assessment may suggest that no risk has been identified, in which case, no corrective action is required. However, the risk assessment will have to be reconsidered every time the site conditions or use change significantly.

In summary, the results of the risk assessment can be used to determine the need for remediation and to aid the evaluation and selection of remedial measures. Such risk-based assessments have to be carried out in close consultation with the regulatory body. By focusing attention on the identified risks, it may mean that only part of the site has to be remediated - thus saving time and money. The use of the risk-assessment approach may also enable more appropriate and readily achievable remediation objectives to be agreed.

The Guidelines for Environmental Risk Assessment and Management. **Department of the Environment, Transport and the Regions (DETR); Environment Agency; and the Institute for Environment and Health. July 2000. Copies are available from: The Stationery Office, PO Box 29, Norwich NR3 1GN. Tel: 0870 600 5522. Price £15. Can be downloaded from the DETR web site (www.environment.detr.gov.uk/eramguide/index.htm).**

Methodology for the Derivation of Remedial Targets for Soil and Groundwater to Protect Water Resources **costs £20 from the Environment Agency's R&D Dissemination Centre at WRc plc (Tel: 01793 865138; http://www.wrcplc.co.uk). To help determine remedial targets for a particular site, purchasers of the report can download a spreadsheet from www.environment-agency.gov.uk/gwcl/index.htm.**

Options for remediation

Having identified a need to treat contaminated land, the next step is to identify the most appropriate treatment technology. There are a number of technologies available to deal with the wide range of pollutants responsible for land contamination. Treatment options can be divided into containment, separation or destruction (see Fig 1).

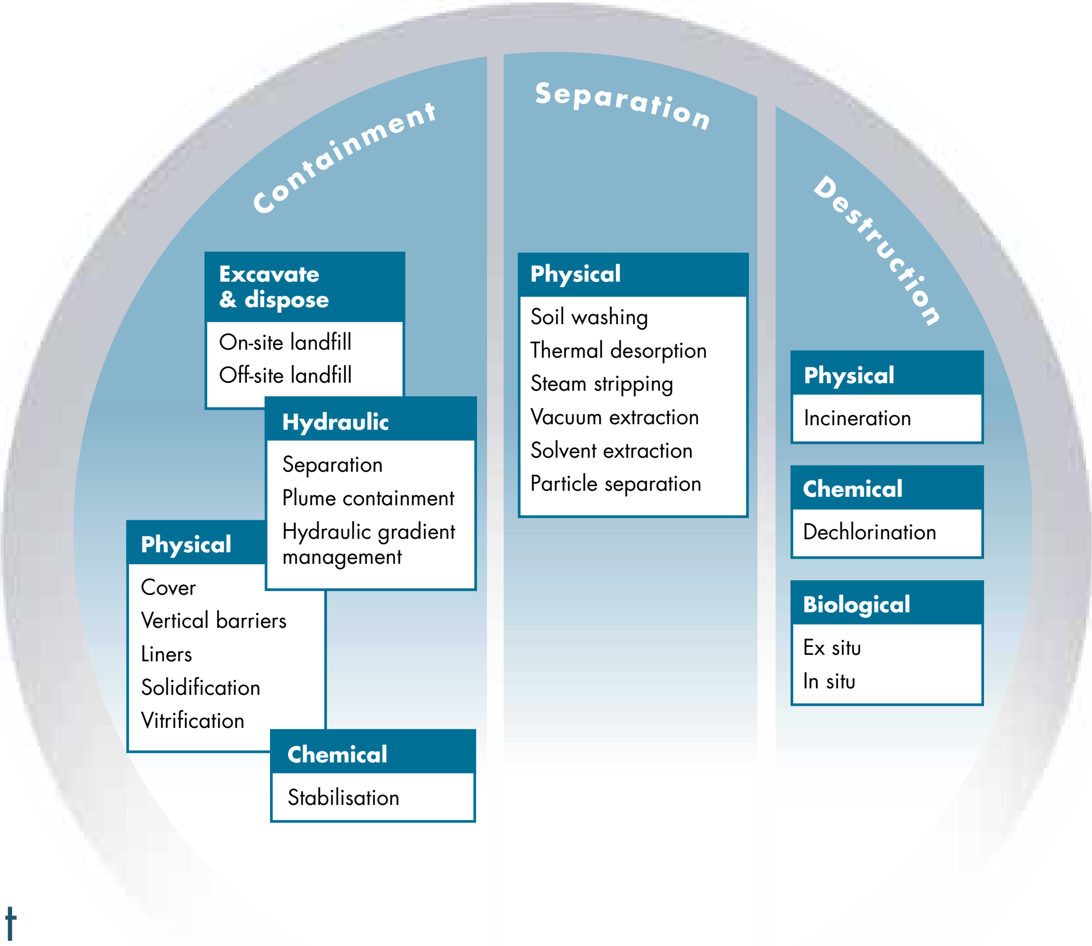


Fig 1
Contaminated land treatment options

Containment

Containment options involve establishing a physical barrier between the pollution and the potential receptor. Containment options are summarised in Table 1.

Table 1
Containment options

Process	Appropriate application areas and contaminants	Limitations	Comparative UK cost
Landfilling	Organics and inorganics	May not meet regulatory requirements	Low/medium (depending on location and type of contaminant)
Barrier/ encapsulation	Organics and inorganics	Waste is not treated	Medium
Vitrification	Organics and inorganics	Limited volume application	High
Stabilisation/ solidification	Organics and inorganics	Not effective with waste containing mostly organic compounds; may break down in the long-term	Low

Separation

Various techniques are available to separate the contamination from the soil, allowing the pollutant to be treated and the cleaned soil to be re-used. Separation and concentration techniques are summarised in Table 2.

Table 2
Separation and concentration techniques

Process	Appropriate application areas and contaminants	Limitations	Comparative UK cost
Pump and treat	Permeable geology with mobile contaminants	Long timescales to address absorbed contamination	Low/medium
Soil washing	Contaminant-specific organic or inorganic waste	Wash solution must be treated; contaminated soil preparation still required	Medium
Soil venting	VOCs	Reliant upon good in-situ ground permeability	Medium
Steam stripping	VOCs	Condensate must be treated	Medium
Low temperature	VOCs	Limited volume application	Medium/high

Destruction

Destruction techniques involve the use of incineration, chemical or biological techniques to change the nature of the contaminants, usually converting them to CO_2 and water. Incineration involves high-temperature treatment of the soil, usually in a rotary kiln arrangement. Destruction techniques are summarised in Table 3.

Table 3
Destruction techniques

Process	Appropriate application areas and contaminants	Limitations	Comparative UK cost
Incineration	Broad range of organic compounds, VOCs, PCBs and petroleum-based waste	Concentrates inorganic contaminants; low-volume process; destroys soil	High
Chemical destruction	Specific organic contaminants (eg PCBs and chlorinated benzenes)	Detrimental effect on soil	Medium
Bioremediation	Organic compounds	Contaminant-specific; can take longer than alternatives	Low/medium

Costs for remediation options

With the highly site-specific nature of the treatment of contaminated land, the cost of treatment will be totally dependent upon local circumstances. To find out up-to-date costs for remediation technology for your site, the best approach is to contact an appropriate supplier. Table 4 presents a comparison of costs for a range of remediation techniques.

Table 4
Comparison of typical costs for a range of remediation techniques

Technique	Range of costs
Bioremediation	£1 - 150/m^3 (see Table 6 for further details)
Stabilisation/solidification	£10 - 100/m^3
Soil washing	£15 - 40/m^3
Barrier/encapsulation	£20 - 180/m^3
Landfilling	£30 - 75/m^3
Incineration	£100 - 400/m^3

What is bioremediation?

Bioremediation can be defined as the elimination, attenuation or transformation of polluting or contaminating substances by the use of biological processes, to minimise the risk to human health and the environment.

Bioremediation of contaminated soil and water uses microbes (eg bacteria and fungi) to convert pollutants to harmless or more environmentally acceptable products. This minimises the risk to human health in a natural or managed process. It makes use of the ability of naturally occurring microbes to degrade a wide range of organic contaminants. In most cases, bioremediation relies on different combinations of indigenous microbes to deal with different pollutants.

However, bioremediation can only stimulate the biodegradation of organic pollutants that are susceptible to microbial attack. As the technology develops, the range of chemicals that can be readily degraded is continually increasing. The current list of chemicals that can be biologically treated includes:

- chlorinated solvents
- petroleum hydrocarbons (eg petrol, diesel, heating oil, fuel oil, crude oil and lubricants)
- aromatic hydrocarbons (eg benzene, toluene, ethylbenzene and xylene (BTEX))
- phenols
- polyaromatic hydrocarbons (PAHs)
- oxygenated hydrocarbons (eg glycols, surfactants and detergents)
- pesticides, dyes and some explosives.

Under aerobic conditions (ie in the presence of oxygen), organic molecules are eventually converted by microbes to CO_2, water and microbial cell mass. Under anaerobic conditions (ie in the absence of oxygen), the final degradation products are often methane, CO_2, hydrogen and microbial cell mass. Complete degradation of organic pollutants in this way is called 'mineralisation'. Partial degradation is also possible, leading to the generation and possible accumulation of intermediate by-products.

Factors to enhance the success of bioremediation

In many cases, bioremediation offers significant cost and environmental benefits over other remediation options. However, its success depends on understanding the nature of the problem and obtaining a thorough knowledge of a site's characteristics (eg its microbial community and the nature, amount and distribution of pollution). A good site investigation is essential to determine the extent of the contamination, site-specific constraints and the potential for microbial activity. In this way, it will provide the information needed to select the most appropriate remediation strategy for that particular site.

Critical factors affecting microbial activity, which can be controlled to enhance biodegradation, include:

- temperature: bioremediation can usually work between 5 - 50°C, but the optimum temperature is in the range of 15 - 30°C
- pH: commonly, the optimum is between 5 - 9
- oxygen concentration: for successful aerobic biodegradation oxygen should be present at >2 mg/litre, but the presence of oxygen can be toxic where anaerobic bioremediation is the principal biodegradative process
- the presence of nutrients (eg nitrogen, potassium phosphorus and trace elements): typically, values of ~1 - 5% nitrogen by weight of oil have been used with the ratio of nitrogen:phosphorus of between 5 - 10:1)
- moisture content: 30 - 80% by weight of the water-holding capacity.

For success, the organic compounds present in the contaminated soil must be both biodegradable and available for biodegradation. The bioavailability of organic compounds is influenced by the solubility of the contaminant and its adsorption onto soil organic and inorganic matter. Generally, the longer contamination remains in the soil, the less bioavailable it tends to be. Therefore, an assessment of the bioavailability of the contaminants is advisable before treatment, particularly for 'aged' contamination.

The geology and hydrogeology of the site are also very important. Bioremediation is more difficult in impermeable soils (eg clay that limits the diffusion of oxygen and water) and in soils containing high quantities of organic matter which limit the bioavailability of the contaminants. For example, pollutants in peat are difficult to bioremediate due to the high organic content, anaerobic conditions and low pH. Bioremediation has been successful in sand and gravel, but is not yet recommended for chalk and sandstone aquifers.

Before commencing full-scale work, it can be both prudent and cost-effective to carry out trials to assess the effectiveness of the biological process, and to confirm the ability of the biotechnology to remediate the contamination. These will provide useful information on the design parameters, allowing optimisation of the bioremediation.

To achieve successful remediation, bioremediation projects need to take account of:

- the factors limiting the rate of biodegradation (eg bioavailability, the availability of nutrients and/or oxygen and temperature)
- the presence of toxic organics, heavy metals or cyanides that may inhibit biodegradation
- an extremely heterogeneous contaminant distribution giving rise to 'hot spots'
- limitations of implementing the treatment on site
- undesirable side effects (eg iron precipitation, accumulation of biomass or mobilisation of heavy metals in the soil)
- the ability of the treatment to achieve the remedial objectives, within any time constraints
- the inability of indigenous microbes to degrade the contaminants present
- regulatory requirements.

Certain compounds do not currently respond to bioremediation, some will be biodegradable in certain circumstances and others are more readily biodegradable, as shown in Table 5.

Table 5
Biodegradability of selected compounds

Currently unable to be biodegraded	Biodegradable in certain circumstances	Biodegradable
• Bitumen	• Explosives	• Diesel
• Asphalt	• Timber treatments	• Jet fuel
• Inorganic acids	• PCBs	• Paraffin
• Asbestos	• PAHs	• Ammonia
	• Tars	• Crude oil
	• Chlorinated solvents	• Lube oil
	• Pesticides/herbicides	• Petrol
	• Cyanides	• Fuel oils
		• Phenols
		• Chlorophenols
		• Creosote
		• Glycols
		• Alcohols
		• Acids
		• Aldehydes
		• Ketones
		• Surfactants

Metals and radionuclides are not biodegradable. Under certain circumstances, the speciation of metals and radionuclides can be altered, resulting in mobilisation or immobilisation of the contaminant, often leading to effective remediation.

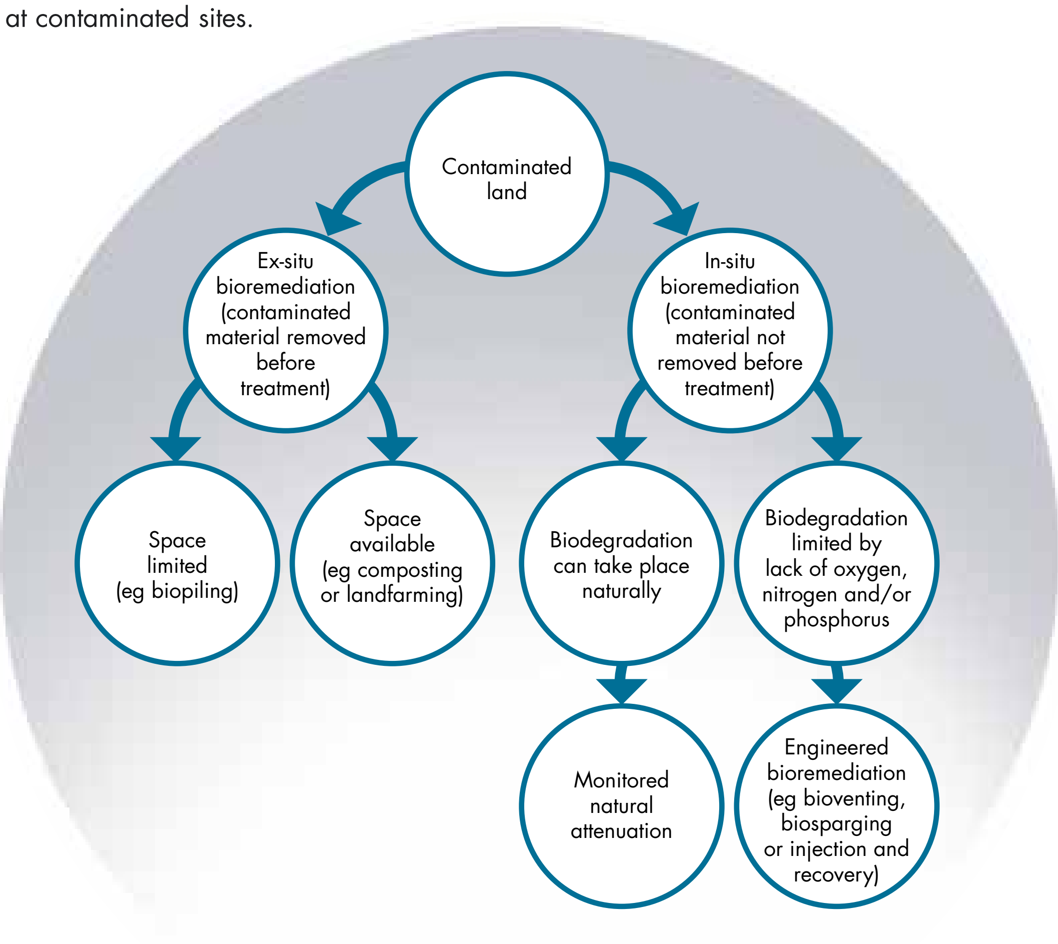
Bioremediation technologies available

Over the last 15 years, bioremediation has become a tried-and-tested method for treating contaminated land and groundwater. All of the technologies discussed in the following sections are commercially available in the UK. They are used predominantly to treat biodegradable organic contamination. The vast majority of commercial applications of bioremediation in the UK have been to treat hydrocarbons (such as petrol, diesel, fuel oils, PAHs and crude oil) and oxygenated hydrocarbons (such as alcohols and aldehydes). In the USA, Netherlands and Germany, bioremediation has also been used successfully to treat chlorinated solvents, timber treatments, pesticides and explosives. At the moment, the UK has only a limited track record regarding the bioremediation of these contaminants. Injection and recovery (also called pump and treat) and bioreactor systems could potentially be used to remove metals from soil and groundwater, although, again, there are few examples of this being carried out in the UK.

Commercial bioremediation technologies for the treatment of contaminated land and groundwater can be divided into ex-situ and in-situ treatment methods. Ex situ means excavating the soil before treatment, whereas in situ means the soil remains in the ground throughout the treatment. There is a wide spectrum of approaches ranging from minimum intervention in-situ techniques (eg monitored natural attenuation) to more expensive ex-situ reactor-based systems. The following sections provide a brief review of the range of bioremediation technologies available.

Fig 2 summarises the use of biotechnology to treat organic pollutants in different situations at contaminated sites.

Fig 2
Bioremediation techniques



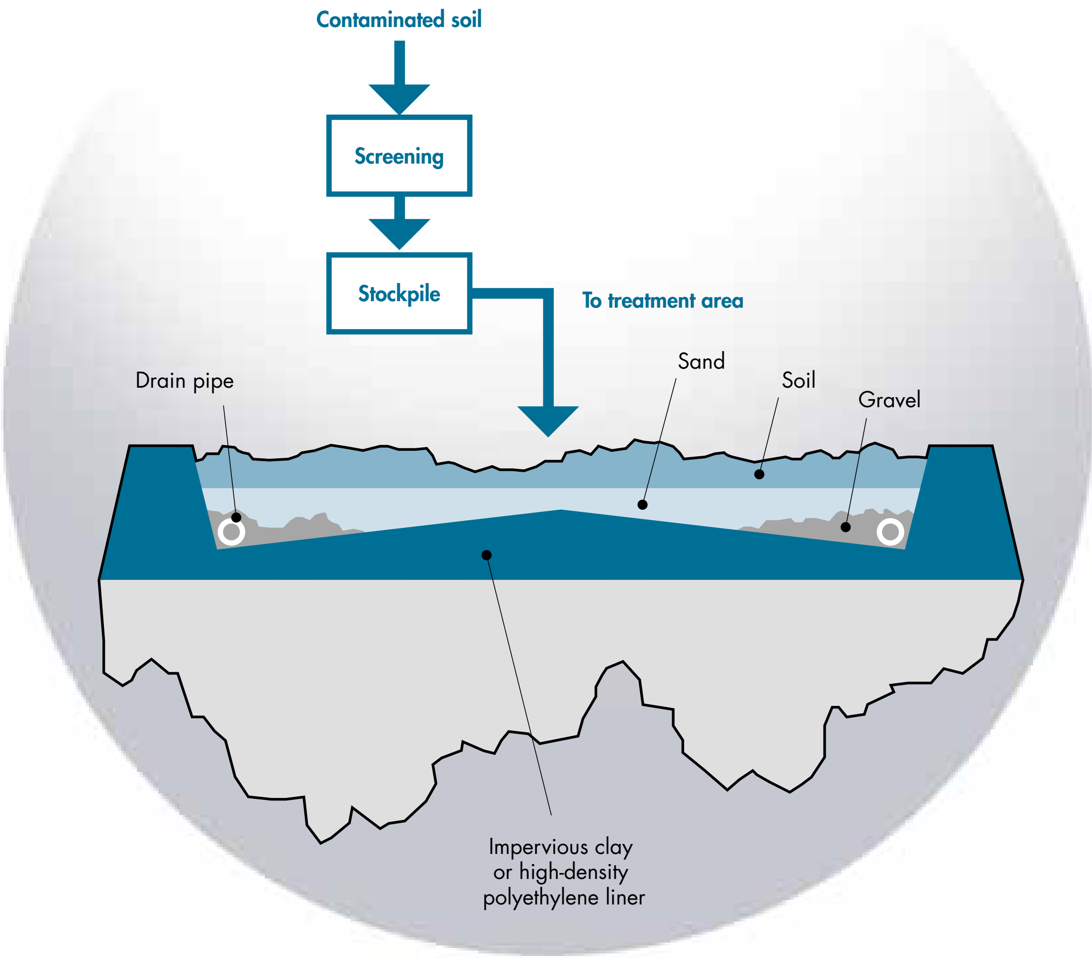
Ex-situ bioremediation technologies

The main technologies are:

Landfarming. Landfarming is particularly suited to the treatment of hydrocarbon-contaminated surface soils and is already used in the UK. The contaminated soil is excavated and screened to remove bulky items such as rubble, metal and plastic. These are usually not highly contaminated and can be considered for re-use as backfill on the site. If contaminated, they may require removal to landfill. The contaminated soil is then spread in a bunded area lined with an impermeable material such as clay or high-density polyethylene (see Fig 3). Water and nutrients are added to stimulate biodegradation and the soil is aerated by regular tilling or ploughing.

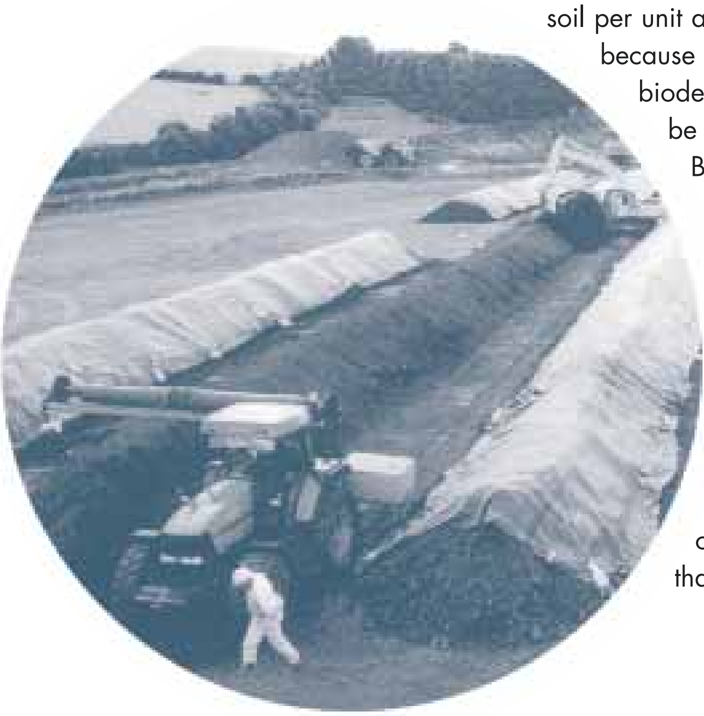
Landfarming is an inherently simple process. However, the effectiveness is particularly dependent on the soil properties, the nature and concentration of the contaminants, the available space for on-site treatment and the climatic conditions. For example, it is more difficult to ensure even aeration and uniform nutrient distribution in heavy clay soils. Soil pH can be adjusted to around neutral by adding lime or elemental sulphur. In cold conditions, soil can be covered to maintain the temperature in the optimum range for bioremediation, ie 15 - 30°C.

Fig 3
Schematic representation of landfarming



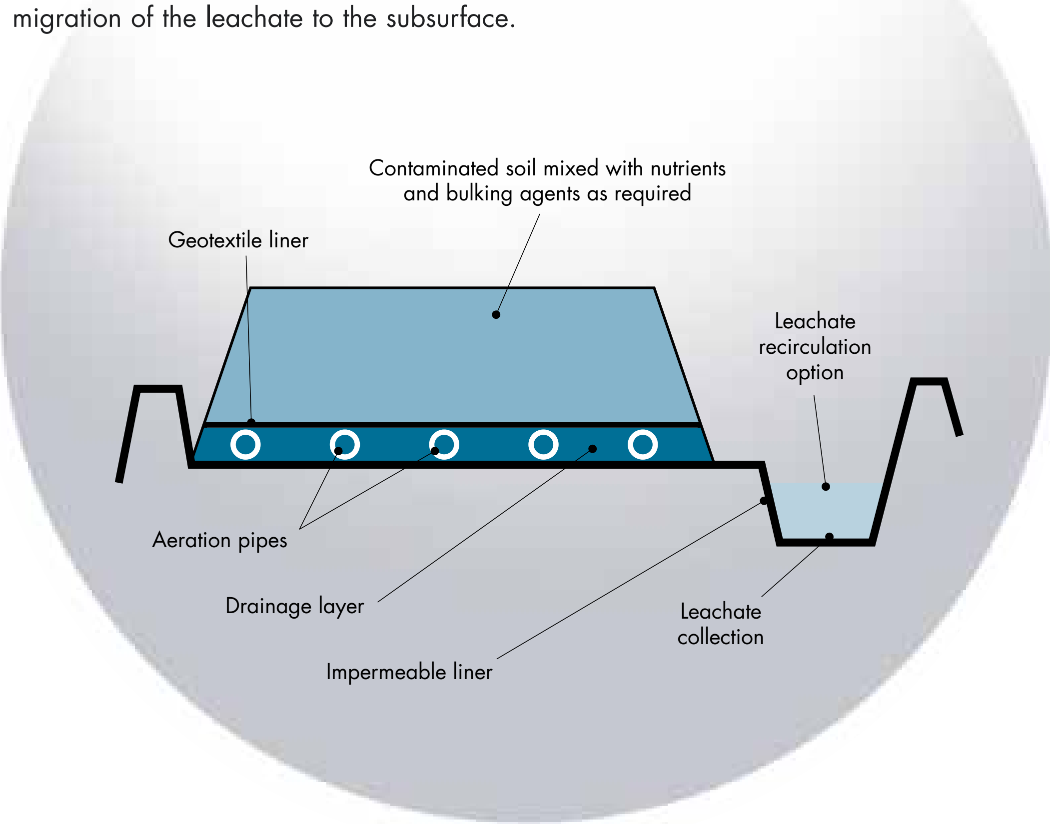
Composting (or soil banking). Composting is also suited to the treatment of hydrocarbon-contaminated soils. Long windrows (rows of excavated and screened soil) are formed outdoors on an impermeable surface (see Fig 4). The rows, which may be covered with straw or a man-made cover to conserve heat and maintain the optimum conditions, are turned periodically using a tractor or other mechanical method to aerate and homogenise the contaminated soil. Composting can treat more soil per unit area than landfarming and, because the heat generated during biodegradation is retained, it can be suitable for colder climates. Bulking agents such as straw, wood chips or other organic matter (eg animal manure) may be mixed with the contaminated soil to improve texture, ease of aeration, water-holding capacity and organic matter content. Biodegradation by composting is generally faster than landfarming.

Fig 4
Composting in windrows



Engineered biopiling. This more intensive version of composting is particularly suitable when space is limited. It aims to optimise the biodegradation process (see Fig 5) through greater control of oxygen, water and nutrient levels. The contaminated soil is mixed with nutrients and bulking agents as required and formed into a pile on top of a drainage layer on a lined, impermeable bunded area. A network of linked pipes in the drainage layer or the soil pile allows air to be sucked or blown through the biopile (either continuously or periodically) to ensure complete aeration. This also allows greater control of VOCs. Leachate from the biopile is collected and sprayed back onto the pile to keep the soil moist. A geotextile liner and sand/gravel layer prevent the contaminated soil coming into contact with the aeration pipes and the drainage layer, and also prevent migration of the leachate to the subsurface.

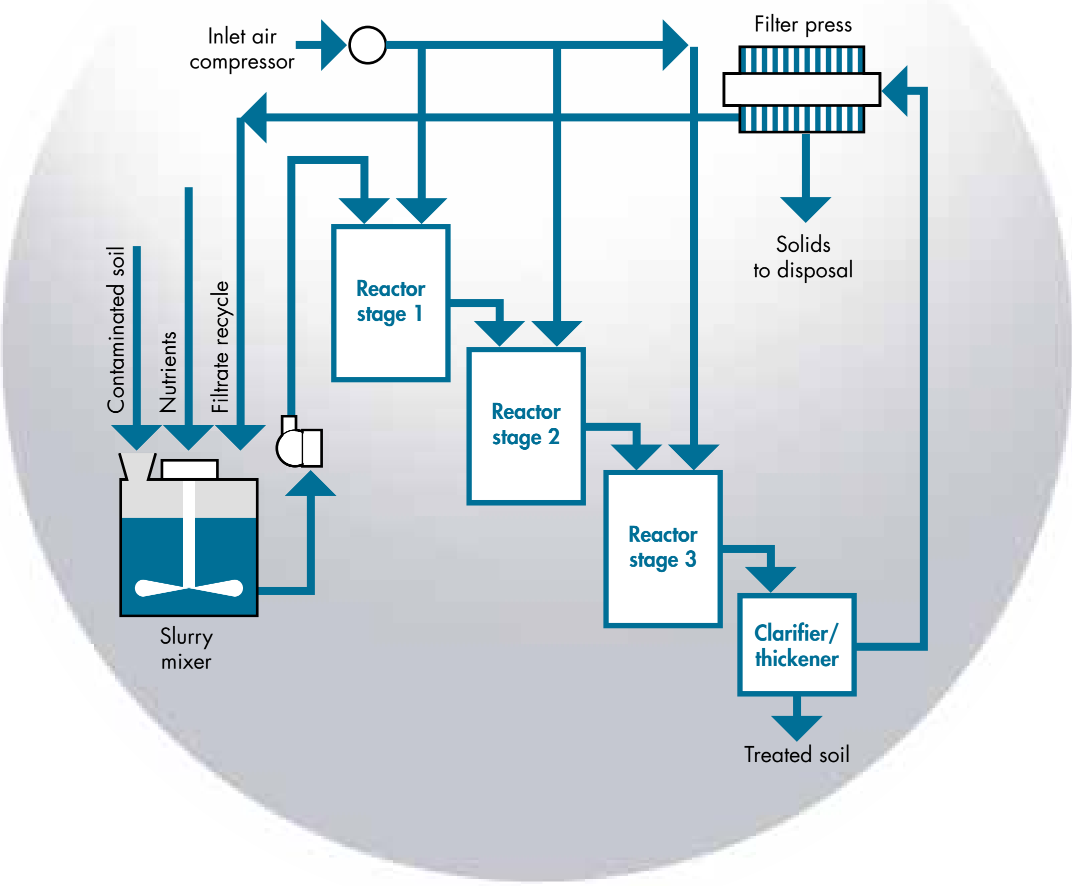
Fig 5
Schematic of an engineered biopile



Bioreactor treatments. When treating complex mixtures of compounds, it may be more effective to combine different treatments in a series of reactor vessels (see Fig 6). Depending on the nature of the contaminants, this series may involve a sequence of aerobic and anaerobic reactors or one involving a combination of different chemical and biological processes. The optimum sequence is determined through trials performed during the feasibility stage.

Typically, the process will involve contaminated soil being mixed with nutrients and recycled filtrate before passing to a sequence of reactors. In each reactor, conditions are maintained to optimise specific biological processes and degrade particular contaminants.

Fig 6
Schematic representation of an example multi-stage system



In-situ bioremediation technologies

The advantage of in-situ technologies is that they do not involve the excavation or removal of soil. The choice between letting nature do the work (a process referred to as monitored natural attenuation) or using an engineered in-situ method will depend on factors such as:

- the identified risks
- the availability of oxygen, nitrate or sulphate for sustaining natural biodegradation processes
- biodegradability of the contaminants
- microbial activity of indigenous microbes.

Monitored natural attenuation. If natural processes within the polluted area are effective in stabilising or reducing the size of a contaminated groundwater plume, then a remedial approach called monitored natural attenuation (also known as intrinsic remediation, passive remediation or bioattenuation) can be considered provided there are no unacceptable impacts or risks to receptors. This technique involves monitoring the natural physical, chemical and biological processes in soil and groundwater that are used to destroy the pollutant or limit its spread or migration. In-situ monitoring and modelling are used to enable the rate of attenuation and the rate of migration of the pollutant to be predicted with some degree of confidence. Long-term monitoring is then used to ensure that the attenuating process will continue to be effective in protecting the water environment and thereby achieve the remedial objectives. Natural attenuation is potentially less expensive than active intervention and requires less site disturbance, but generally takes longer.

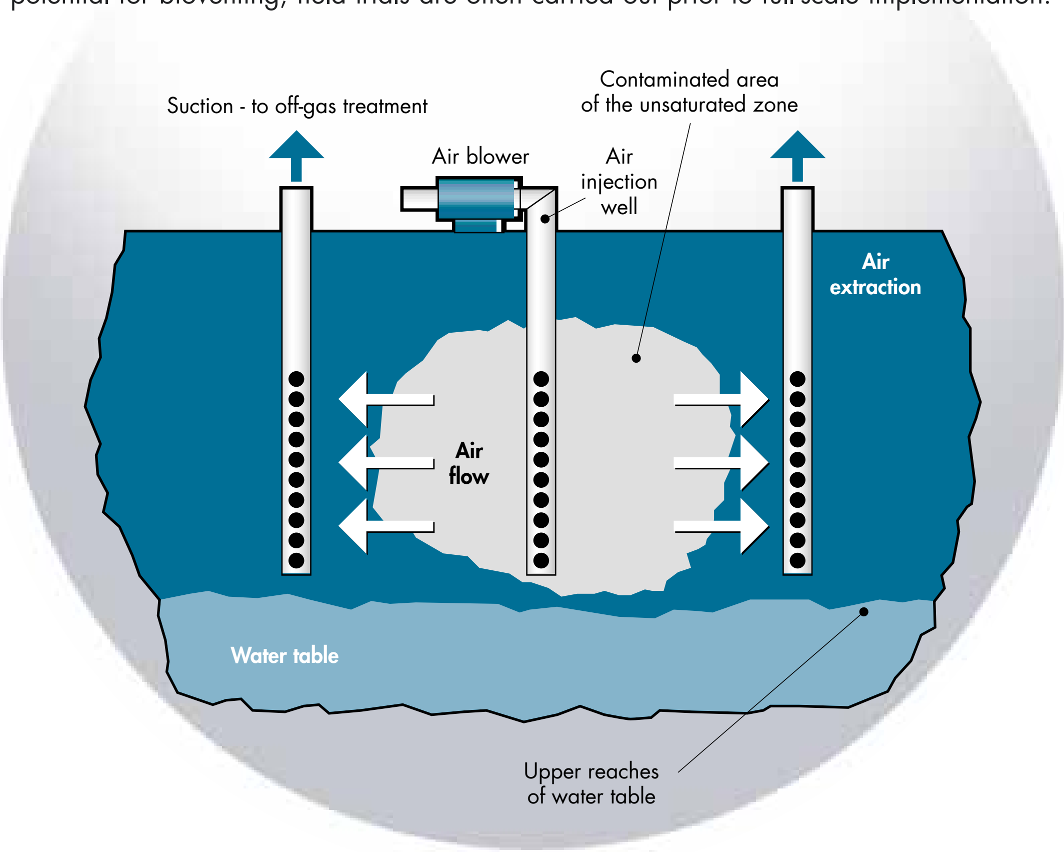
For more information on natural attenuation please consult the Environment Agency's R&D Publication 95 *Guidance on the Assessment and Monitoring of Natural Attenuation of Contaminants in Groundwater*, available from the Environment Agency's R&D Dissemination Centre at WRc plc (Tel: 01793 865138; http://www.wrcplc.co.uk).

In-situ engineered bioremediation techniques involve various methods of introducing oxygen and nutrients to the contaminated area. Some cases include the surface treatment of contaminated water and vapours. The main methods, which all depend on modifying conditions within the soil or groundwater, are:

Bioventing. This method uses indigenous microbes to biodegrade organic contaminants in the unsaturated zone (ie above the water table). It combines supplying extra oxygen with vapour extraction to promote air flow through the contaminated area and enhance natural biodegradation. Air is blown into the centre of the area of contaminated soil above the water table and sucked out through peripheral boreholes to off-gas treatment prior to emission to atmosphere (see Fig 7). To enhance the biological process, nutrients can be blown into the contaminated area. The injection of oxygen stimulates the microbes in the contaminated soil to degrade the organic contaminants to CO_2 and water. The process also mobilises volatile compounds (either present in the soil or produced during biodegradation) to move towards the boreholes, making extraction simpler. However, in many bioventing treatments, the aim is to adjust the air extraction rate to maximise subsurface decomposition and minimise the need for surface treatment of volatile compounds.

Soil structure and stratification are important because they affect how and where vapours flow within the soil matrix. Air flow is reduced if water blocks the soil pores. As diffusion may be slow in some soil types, tracer studies can be used to study the flow of air away from the injection point before treatment begins. Permeable, well-aerated soils (eg sand or gravel) are the most suitable for bioventing. Bioventing is not generally appropriate for sites where the water table is less than one metre below the surface. To assess the potential for bioventing, field trials are often carried out prior to full-scale implementation.

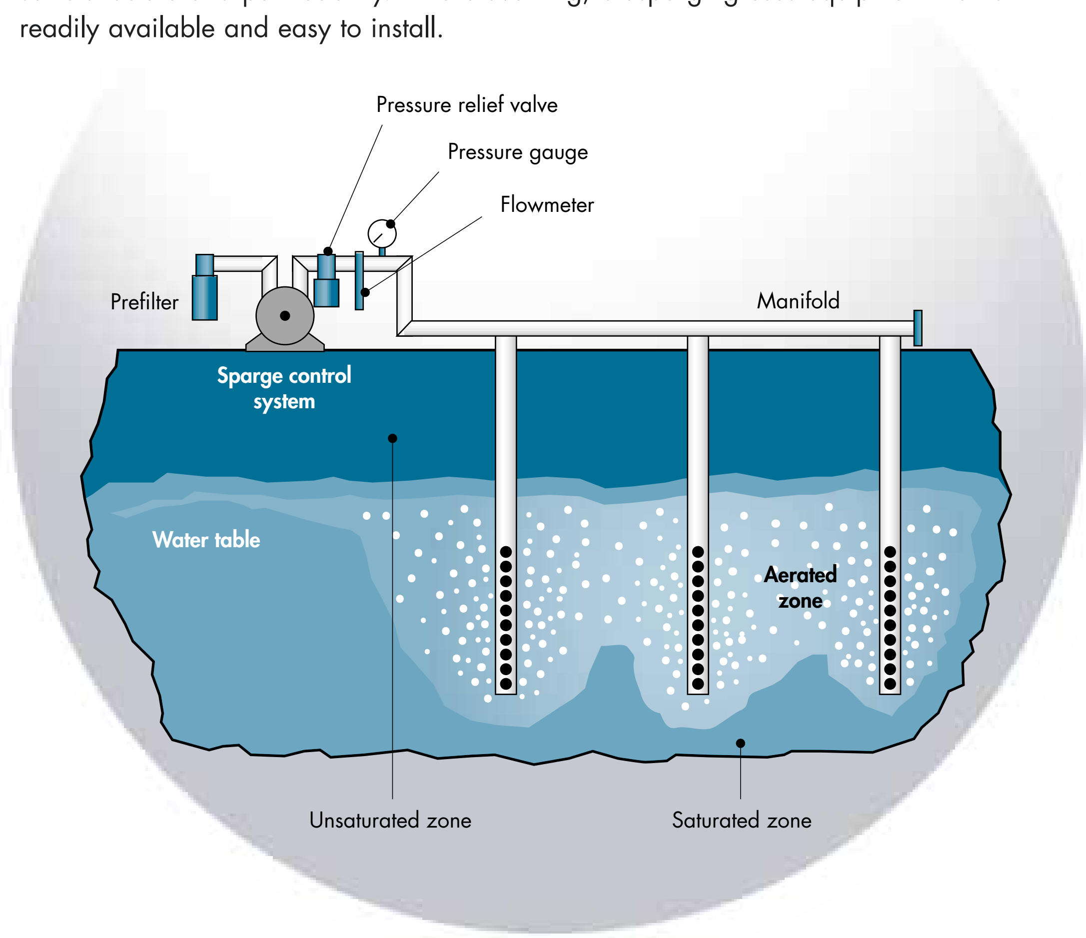
Fig 7
Schematic representation of a bioventing system



Biosparging. This method uses naturally occurring microbes already present to biodegrade organic contaminants in the saturated zone (ie below the water table) and potentially in the overlying unsaturated zone. This process involves increasing the supply of oxygen to the contaminated soil by injecting air into the saturated zone via boreholes (see Fig 8). As with bioventing, nutrients may be added to enhance the biological process. The air forms small bubbles in the groundwater, encouraging oxygen dissolution in the groundwater and transport of air to the overlying soil. This encourages aerobic biodegradation of contaminants dissolved in the groundwater and contaminants present in the soil. The technique's success depends on adequate diffusion of the injected air away from the boreholes into the surrounding groundwater and soil. Many bioremediation companies will carry out tracer studies before commencing biosparging operations.

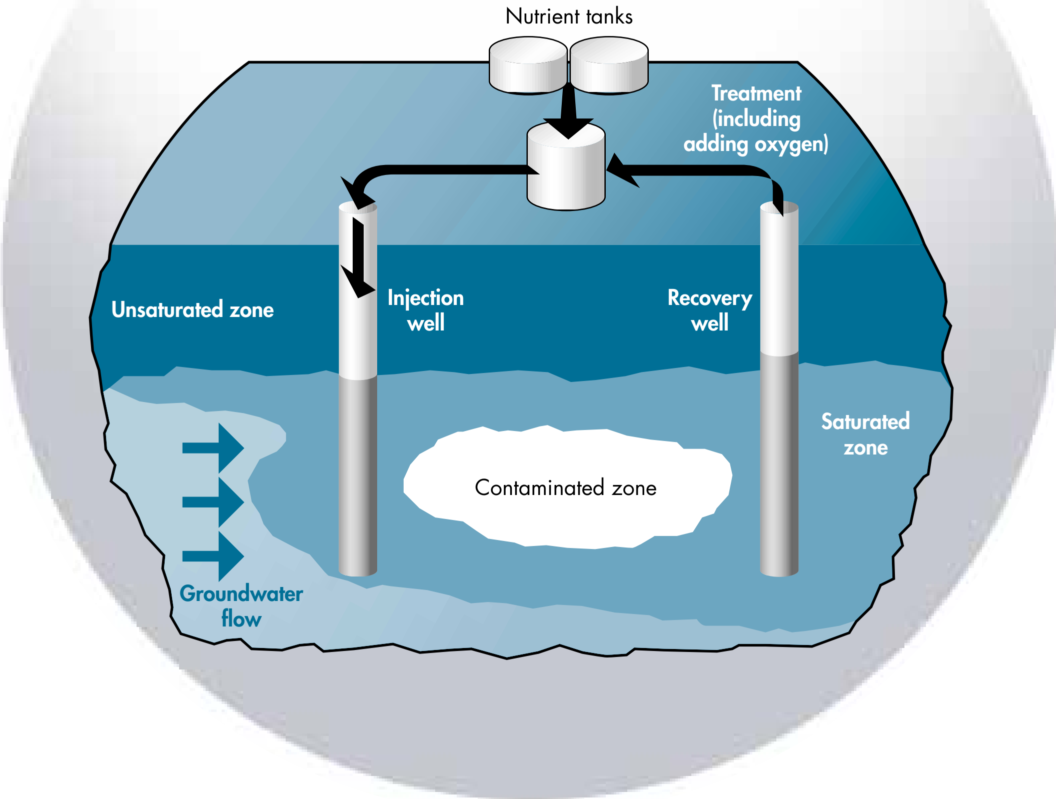
As with bioventing, the effectiveness of biosparging depends on the overlying soil's permeability (and thus the rate of air flow through the soil) and obtaining optimum conditions for microbial growth in terms of temperature, pH and the presence of sufficient nutrient levels. The location and number of boreholes depend primarily on the subsurface soil's structure and permeability. Like bioventing, biosparging uses equipment that is readily available and easy to install.

Fig 8
Schematic representation of a biosparging system



Injection and recovery systems (or pump and treat). These systems aim to create a bioreactor in the medium to be treated. The contaminated aqueous phase from the saturated zone is pumped, via a recovery well, to a treatment tank on the surface. In the treatment tank, nutrients, oxygen and other electron acceptors (eg sulphate and nitrate) are added before the groundwater is pumped back into the ground via an injection well and recirculated through the contaminated zone (see Fig 9). The oxygen and nutrients in the injected groundwater stimulate the microbes present in the contaminated zone to biodegrade contaminants dissolved in the groundwater and present in the soil. Groundwater extraction and injection continue until monitoring data show that the remedial objectives have been achieved.

Fig 9
Schematic representation of an injection and recovery system



Costs of Bioremediation

A key factor in selecting a remedial technology is the cost of its implementation. Although the precise cost of treatment will be heavily dependent on site-specific conditions, a general indication of the costs of the bioremediation technologies discussed in previous sections is given in Table 6.

Table 6
A comparison of costs for bioremediation technologies

Technology	Cost/m^3
Landfarming	£10 - 40[1]
Composting	£10 - 30
Biopiling	£10 - 40
Natural attenuation	£1 - 25[2]
Bioreactors	£30 - 150[3]
Bioventing	£10 - 50
Biosparging	£10 - 30
Injection and recovery	£5 - 80[4]

[1] Landfarming will be cheaper if existing facilities are used.

[2] Large sites may be even cheaper than £1/m^3. A more effective way of costing natural attenuation may be to use a cost of £500 - 700 per borehole per monitoring event.

[3] The costs will be highly dependent on the type and the volume of the contamination. The treatment of low volumes will be expensive.

[4] Cost for groundwater treatment only.

New developments in bioremediation

A number of new in-situ and ex-situ bioremediation techniques are showing promising results in commercial trials. It may be that the application of these developing techniques will offer even greater commercial benefits in treating contaminated land. Possible methods which could be used in the UK over the next few years include:

Bioaugmentation. This technique involves adding selected micro-organisms to degrade the contamination. Bioaugmentation depends on the correct identification of micro-organisms to deal with the specific contaminant, their effective addition, and their ability to survive in competition with existing indigenous micro-organisms in the contaminated environment. The technique is likely to be most effective on the rare occasions where there are no indigenous micro-organisms capable of degrading the contaminants.

New forms of nutrient and electron acceptor. Bioremediation can be enhanced by adding advanced forms of nutrients for stimulating microbial action. Examples of new forms of nutrient include gas or vapour-phase nutrients such as nitrous oxide and triethyl phosphate, oleophilic nutrients for the treatment of hydrophobic contaminants, and mineral, slow-release fertilisers. Another development includes the use of slow-release oxygen compounds to enhance aerobic bioremediation.

New ways of delivering nutrients. These include:

- combination wells that allow simultaneous delivery and/or abstraction of liquids and gases
- horizontal or angled wells for use beneath buildings
- fracturing less permeable geological structures to promote nutrient flow.

Co-metabolism. This involves adding a co-substrate which supplies energy to help indigenous microbes degrade contaminants in situ. This has been used successfully in the US for the in-situ treatment of chlorinated solvents.

Anaerobic processes. Certain synthetic compounds (eg chlorinated solvents) have been found to degrade more rapidly and more completely either in situ or ex situ, in the absence of oxygen. When treating mixed organic and inorganic contamination, anaerobic processes can have the advantage of immobilising some heavy metals by precipitating the metals as their respective sulphide. This process has been used successfully in the US.

Phytoremediation. This involves the use of plants to remove contamination from soil, such as through the accumulation of metals and the degradation of organic contaminants by microbes in the plants' roots. Commercial applications of this technology are underway in the UK.

Ex-situ versus in-situ bioremediation

The assessment of whether in-situ or ex-situ bioremediation represents the best option will be highly site specific. Table 7 shows a general comparison to assist the assessment. Site owners are recommended to discuss both approaches with bioremediation suppliers.

Table 7
Comparison of ex-situ and in-situ techniques

Technique	Advantages
Ex-situ	• Generally quicker than in-situ techniques • Can deal with high concentrations of contamination • Particularly suited to shallow contamination • Easier to control • Remediation conditions can be optimised • Predictable timescales • Readily contained in a controlled area
In-situ	• Able to deal with deep contamination • Avoids expensive excavation • Allows remediation around or under buildings without disturbance • Reduces worker exposure to volatile compounds • Minimises problems with dust

Further information

To find out more about how bioremediation could help your company, contact the BIO-WISE Helpline on freephone 0800 432100. The Helpline can:

- send you details of UK suppliers of bioremediation services
- put you in touch with an industrial biotechnology specialist who can provide you with more information about bioremediation technologies
- send you free copies of Case Studies of companies that have successfully applied bioremediation and other relevant publications including the quarterly BIO-WISE newsletter
- tell you about other sources of help and information.

Use the Helpline to find answers to your queries about bioremediation and to access free, practical advice on how biotechnology makes companies more competitive.

In addition, further information on bioremediation can be obtained from the following sources:

- **CL:AIRE**

  CL:AIRE is a public/private partnership which acts as a link between the main players in contaminated land remediation in the UK. It acts to catalyse the development of cost-effective methods of investigating and remediating contaminated land in a sustainable way.

  Contact:
  CL:AIRE
  29 Bressenden Place, London SW1E 5DZ
  Tel: 020 7316 6269
  Fax: 020 7316 6141
  Web site: www.claire.co.uk

- **CIRIA**

  6 Storey's Gate, London SW1P 3AU
  Tel: 020 7222 8891
  Fax: 020 7222 1708
  Web site: www.ciria.org.uk

Other interesting bioremediation-related web sites include:

Biotechnology and Biological Sciences Research Council
www.bbsrc.ac.uk

Environment Agency
www.environment-agency.gov.uk

Network for Industrially Contaminated Land in Europe (NICOLE)
www.nicole.org

Contaminated Land Rehabilitation Network for Environmental Technologies (CLARINET)
www.clarinet.at

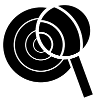
The Contaminated Land Assessment and Remediation Research Centre (CLARRC)
www.clarrc.ed.ac.uk

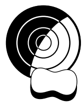
exSite Research
www.exsite.org

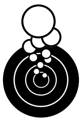
The BIO-WISE web site (http://www.dti.gov.uk/biowise) can provide you with information on a wide range of uses of biotechnology. Visit the site and look for the following icons:

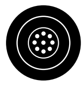
 ***raw materials***

 ***in-process***

 ***monitoring***

 ***cleaning***

 ***air emissions***

 ***wastewater***

 ***bioremediation***

 ***solid waste***

Glossary

Aeration	Incorporation of air into a liquid or solid material by exposure (passive), mixing, agitation, chemical means or direct injection with the aim of transferring oxygen to the material.
Aerobic	Living or acting only in the presence of oxygen.
Anaerobic	Living or acting only in the absence of oxygen.
Attenuation	The process of reducing in concentration.
Bioavailability	The availability of contaminants to microbial attack.
Biodegradation	The breakdown of materials by the action of microbes.
Bioremediation	The elimination, attenuation or transformation of polluting or contaminating substances by the use of biological processes, to minimise the risk to human health and the environment.
Brownfield site	A site that has previously been developed for residential, commercial or industrial use.
Electron acceptor	A compound required by organisms to be able to decompose food and convert the food into energy. Humans use oxygen in air for this purpose.
Ex-situ treatment	Treatment of contaminated soils and groundwater out of, or removed from, their original position (ie requires removal or excavation of the soil from the ground).
Greenfield site	A site that has not previously been developed for residential, commercial or industrial use.
Indigenous	Naturally occurring/originating.
In-situ treatment	Treatment of contaminated soils and groundwater where they are found without excavation.
Microbes	Living organisms that can be seen only under a microscope (eg bacteria, fungi, yeasts, protozoa, algae and viruses).
Natural attenuation	The use of naturally occurring physical, chemical and biological processes to immobilise, degrade and remove pollutants.
Pathway	A route by which a receptor is being or could be exposed to, or affected by, a contaminant.
PCB	Polychlorinated biphenyl.

Phytoremediation	The removal of pollutants from soil or water using plants.
Receptor	A living organism, a group of living organisms, an ecological system or a piece of property which is being or could be harmed by a contaminant. Potential receptors include humans, living organisms and ecosystems, livestock, game, fishing rights, crops, buildings and receiving waters, eg groundwater, river water and drinking water supplies.
Remediation	Action taken to mitigate unacceptable risks.
VOCs	Volatile organic compounds. These are carbon-containing chemicals that are emitted or evaporate into the atmosphere. For example, many organic solvents are liquids at room temperature and pressure, but have a low boiling point and thus evaporate readily to air. The Solvents Directive defines a VOC as any organic compound that has a vapour pressure of 0.01 kPa or more.
Windrows	Contaminated soil arranged in rows to enhance natural degradation processes.

BIO-WISE
Biotechnology at work

KEEPING IN CONTACT

BIO-WISE HELPLINE **0800 432100**

Fax: 01235 432997

Web site: http://www.dti.gov.uk/biowise

e-mail: biowise.help@aeat.co.uk

BIO-WISE, PO Box 83, Didcot, Oxfordshire OX11 0BR

Further Help

Contact the BIO-WISE Helpline for free, independent information and advice about bioremediation and/or other types of biotechnology. BIO-WISE can provide access to expert advice from around 30 UK industrial biotechnology specialists. These specialists can provide up to four hours of free advice.

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