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ENVIRONMENTAL BIOTECHNOLOGY - TOOLS FOR A SUSTAINABLE FUTURE?

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Abstract: Throughout history, man has exploited nature to meet his needs. In the last few decades it has become evident that uncontrolled exploitation is unsustainable – anthropogenic pollution and the depletion of non-renewable resources cannot continue if we are to avoid catastrophic events in the coming century. The scope of such environmental problems is broad and their nature complex. This paper discusses the extent to which biotechnology can contribute to the solutions of our environmental problems, and the challenges that face us in developing and implementing both existing and new biotechnologies.

Key words: Sustainable, environment, biotechnology.

Resumen: A través de la historia el hombre ha explotado la naturaleza para satisfacer sus necesidades. En las últimas décadas se ha hecho evidente que la explotación descontrolada es insostenible – la contaminación antropogénica y la desaparición de recursos no renovables – no debe continuar si queremos evitar eventos catastróficos en el próximo siglo. El espectro de tales problemas ambientales es amplio y su naturaleza es compleja. Este estudio discute hasta donde la biotecnología puede contribuir para resolver nuestros problemas de medio ambiente y los desafíos que encaramos en el desarrollo e implementación de la biotecnología existente así como de la nueva.

Palabras claves: Sostenible, medio ambiente, biotecnología.

KEY ENVIRONMENTAL ISSUES

At the root of environmental problems is the continuing growth in human population – particularly in urban areas in the developing world (**Figure 1**).

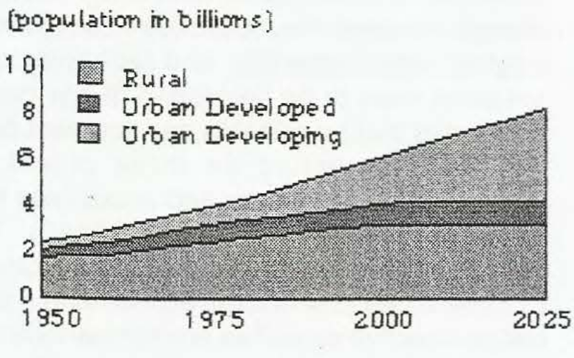

Figure 1. Population growth prediction (WRI 1996)

Modelling of the interaction of human population, activities, resource usage and economic activity predict that without substantial changes in lifestyles the capacity of the earth to support human life will be greatly diminished. For example, it has been predicted that the coming century will see a peak in the world's population followed by a decline caused by food and resource shortage (Meadows et al 1991), as shown in **Figure 2.**

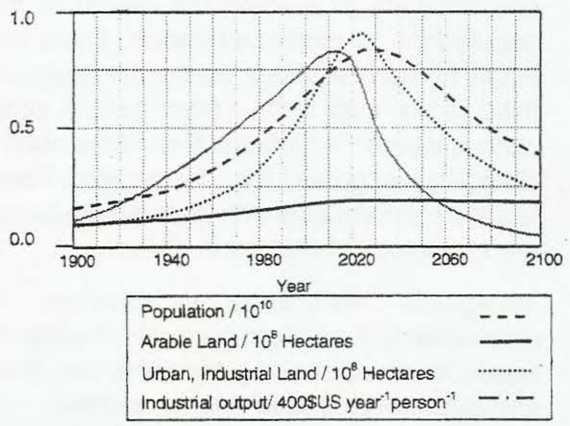

Figure 2. Typical World 3 Model prediction

While such modelling can readily be criticised, it is important to focus not on detail, but the essential message – the current situation is unstable and that action must be taken.

Some critical environmental challenges facing mankind have been identified as (Williams 2000):

- By 2025, two thirds of the people will live in areas where shortage of water is a problem;
- A 60% reduction in greenhouse gas emissions is believed to be required to stabilise climate change;
- A 10-fold reduction in resource use is required if developing countries are to achieve the living standards of the developed world;
- By 2025, the population living in cities will grow by 2.5 million.

Other concerns exist. The accumulation of toxic materials in the environment may reduce soil fertility or have direct toxic effects on mankind. The reduction of biodiversity may remove opportunities identify medical treatments, reduce the ability of the natural environment to respond to stresses and will certainly reduce the aesthetic value of our environment (Lovejoy 2000).

RESPONSES TO THE PROBLEM

While the nature and difficulties of the problem that face us have been analysed, and the consequences of failure are recognised as serious, our response has been tentative. There are many reasons for this. Much of mankind is more directly concerned with the day-to-day issues of survival. Conversely, the richer nations find difficulty in curbing the desire of their populations for increased wealth. There is an innate human belief that the current situation is fixed in the long term – most people simply cannot accept the problem. Even if the need for change is recognised, it is often resisted. People feel more comfortable with what they know, and are suspicious of change in all forms.

Alongside resistance to change, the mechanisms that might generate change are weak. International agreements on global environmental issues are a relatively new phenomenon. For example, the original Montreal Protocol was adopted in 1987 (UNEP Ozone Secretariat 2000), the UN Framework Convention on Climate Change in 1992 (United Nations 2000), under which the Kyoto Protocol of 1997 was developed. These are all recent compared with conventions on War (eg 4th Geneva Convention of 1949) and trade (The agreement of GATT 1947). There is no strong enforcement body on environment similar to others that police different issues – for example the World Trade Organisation. This is particularly ironic as environmental problems are probably more global in nature than the problems of trade.

The concepts that drive the development of global policy and law on environment are relatively recent. The Brundtland report (World Commission on the Environment and Development 1987) that presented the concept of Sustainable development:

> *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs is less than 15 years old."*

Further problems lie in economic and social factors. Current economic systems do not take account of the hidden costs of environmental damage. This means that short-term, environmentally damaging activities appear favourable compared with longer-term sustainable developments. Existing investment in non-sustainable technologies presents a financial and cultural barrier to the introduction of the new. Only recently have governments started to use fiscal policies to drive environmental improvements through, for example, the so-called "Climate Change Levy" in the UK (Saunders 2000).

Another issue is the wide public mistrust of science that potentially inhibits the introduction of new techniques such as genetically modified (GM) crops.

Clearly, many of the issues above lie outside the ability of individual scientists to influence strongly. However, they do provide a background against which scientific and technological solutions need to be developed. It has been suggested that sustainable development can be seen as resting on three pillars – environmental, economic and social (see for example Clift 1998 or Mitchel 2000). To contribute to a sustainable future, a technology must be acceptable from an economic and social perspective as well as environmentally. In what follows, I will be using these three perspectives as tests to assess the viability of particular techniques and technologies.

BIOTECHNOLOGY AND THE ENVIRONMENT

In this lecture I shall be defining Environmental Biotechnology as the use of any organism(s) to solve an environmental problem. Of course, this makes the scope very large, but environmental biotechnology is already big business. For example, biological wastewater treatment is probably the world's the largest industrial process in terms of material throughput.

Broadly, five areas can be identified for the application of environmental biotechnology:

- Biodegradation for pollutant removal and benefaction of effluents and wastes;
- Bioprocessing as a cleaner alternative to current techniques;
- Bioremediation of pollution currently in the environment;
- Biosensing for analysis of environmental problems; and
- Bioresources to provide renewable raw materials for human activities.

We can also divide aspects of biotechnology on the basis of its underlying technical approach:

- Modification of organisms or cultures to deliver particular properties, through selection and/or genetic modification, where the focus is primarily the application of biological science; and
- Exploitation of existing (or new) organisms in designed systems to deliver the best conditions, where the focus is primarily the application of engineering.

This is more along the traditional academic divisions into scientist and engineer. While the modification of organisms is seen as more challenging science, it can be argued that the more important challenges to resolve are in the application of organisms. Indeed, almost all of the value of biotechnology applications to the environment lies in the use of unmodified organisms, or organisms that have naturally adapted to deal with a particular effluent or waste.

BIODEGRADATION FOR EFFLUENT TREATMENT AND WASTE BENEFACTION

A great range of technologies is available for the biological treatment of wastes to reduce its potential for harm. As well as the destruction (mineralisation) of wastes, biological techniques can be used to detoxify wastes and even to make useful products. A short list of just a few current and emerging technologies that illustrates the enormous variety of systems is given in **Table 1**. The message here is the great flexibility and adaptability of biological systems. In this context it is perhaps a recognition of the limitations of bio-systems that brings most insight.

Table 1. Biological waste treatment and benefaction techniques.

Waste type	Technology
Gaseous Volatile Pollutants, odour	Bioscrubbers Biofilters Soil filters
Aqueous wastes (dilute)	Reed beds Wetlands Aerobic digestion-various reactor Types Nitrification/denitrification ponds
Concentrated wastes	Anaerobic digestion (possibly with methane or VFA recovery)
Xenobiotic mixed aqueous wastes	Landfarming (discredited) Membrane bioreactors
Solid wastes	Composting Managed landfill Anaerobic reactors

Two key features of a waste that influence the technical suitability of biotechnology for its treatment are toxicity and concentration. Of these, toxicity is the more important in determining whether a biological system is suitable at all. However, with some ingenuity even highly toxic wastes can be treated by the use of appropriately designed systems. Particularly low waste concentrations will not in themselves provide the energy for biological digestion, and require additional nutrients to work effectively.

The phase(s) (gas, liquid or solid) present in the waste are key determinants in the selection of an appropriate biological system. Just as important as the technical features of the process are the practical questions of cost (both capital and operating), robustness, amount of waste to be treated and stability of waste rate and feed composition.

The important issue of cost is often improperly understood by developers of biotechnologies. Biological waste treatment methods are in competition with non-biological techniques such as incineration, combustion in a cement kiln, precipitation etc. To be effective the biotechnology cost must fall below the cost of competing techniques. Further, sophisticated biological techniques may be in competition with cheaper ones. Often, the cost of waste treatment and disposal – particularly for the relatively dilute wastes where biological techniques have their best performance - is very low, perhaps less than $1 (US) per tonne of waste. Thus, expensive techniques can only be justified where a clear commercial advantage exists, and competing techniques are expensive. It can be argued that the application of sophisticated biotechnologies to the improvement of low-value waste treatment is doomed to failure.

Biological waste treatment systems have a reputation in industry for being unreliable, difficult to operate, vulnerable to shock loading, slow to respond to change and requiring substantial land area. In order to extend the range of capability of low cost biological treatments, combinations of biological and physico-chemical treatments an important theme. One example is the "membrane bioreactor". This uses a membrane to extract biodegradeable materials into a bioreactor while excluding the dissolved inorganics that would kill the organisms (**Figure 3**, Livingston 1993a,b). This technique has been used industrially for treatment of chemical processing effluents.

CLEAN BIOPROCESSING

Clean Processing can be defined as production using fewer raw materials, less toxic raw material, and producing less, or less toxic wastes. Against that definition, there are examples where the use of biologically-based processing is cleaner than its non-biological counterpart. However, enthusiasm for biotechnology must be tempered with caution. Biological methods of production for single chemical substances are often singularly inefficient in terms of raw materials used and effluent volume compared with a non-biological process. For example, while fermentative preparation of alcohol gives up to about 14% solutions, much more typical would be fermentations for production of antibiotics, with yields around 1% or less.

One area where the benefits of bioprocessing has the potential to outperform normal synthetic methods is in the manufacture of complex chiral molecules - as is common in the pharmaceutical and to some extent agrochemical industries. Here, the enantioselectivity of biological catalysis may outperform the very poor yields that can be expected from traditional synthesis.

BIOREMEDIATION

Bioremediation is the decontamination of land by biological techniques. Given the large scale of many contaminated land problems, the relatively low concentrations of pollutant and the high cost of physico-chemical means of cleaning land, there is a substantial opportunity for the bioremediation. A great range of technologies possibilities exist, ranging from in-situ treatment through the treatment of leachate to the removal and treatment of soil off site.

Of course, bioremediation has to compete with other techniques. Typical bioremediation costs in the UK are £16-80 per tonne of soil, compared with techniques ranging from landfilling of the soil (£5-30/tonne) to incineration (£400-1,200 per tonne) (Pritchard 2000).

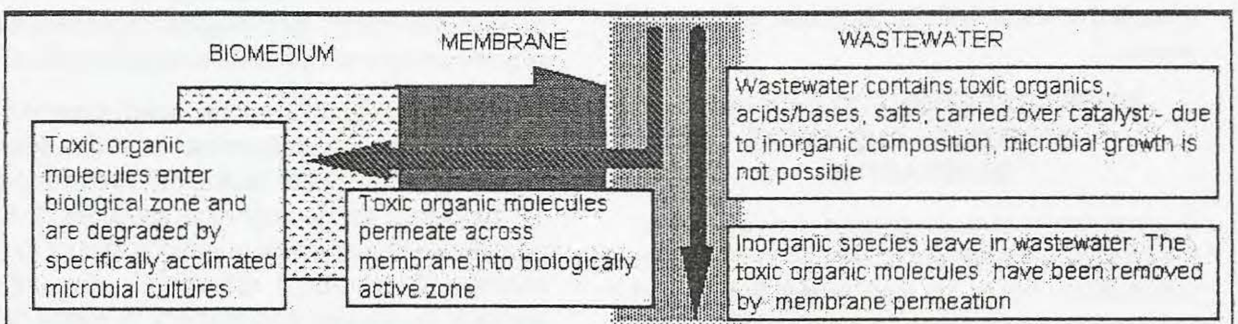

Figure 3. Schematic of membrane bioreactor (Livingston 2000)

A useful source of information about ongoing bioremediation projects is the USEPA, whose BFSS database gives information on about 500 projects (USEPA 2000). A great range of techniques is possible to treat, for example wood preserving wastes, petroleum, solvents, pesticides and munitions. Treatment technologies include reactor treatments (ex situ), aerated lagoon treatment, land treatment, composting, air sparging, bioventing, and many others. By use of exogeneous and possibly modified organisms, the remediation of normally recalcitrant compounds – chlorinated or nitro-substituted for example – is possible.

BIOSENSING

A key problem in dealing with environmental impacts is their assessment and quantification. This arises in applications such as

- Assessment of wastes for their potential for environmental harm as part of new process or product development;
- Assessment of process wastes for their haz ard during process operation;
- Process control (for example control of the influent to a biological treatment works);
- Monitoring of the environment for change re sulting from emissions; and
- Monitoring of the environment to assess accidents.

Unfortunately, traditional biological techniques for the assessment of environmental impact are expensive and time-consuming. Novel biosensing techniques are being developed that bring the prospect of faster, cheaper assessment that at least identifies the potential for major problems. One technique of interest involves the use of a jellyfish gene that induces fluorescence to detect the occurrence of DNA damage. This can be used as a screening test for the presence of materials likely to be mutagenic, and the test can be carried out quickly and cheaply. The UK Environment Agency is actively exploring the use of direct toxicity assessment using this and other rapid screening techniques as a way of setting consents on complex mixed discharges from industrial processes.

BIORESOURCES

The use of biological feedstocks for the industries that currently use fossil fuels is nothing new. Before oil and coal, primitive process economies existed using trees and animal fats as primary feedstocks. However, the lower costs and high concentration of fossil fuel resources make them preferable for modern economies.

While biologically originated fuels (green diesel, biofuels etc.), feedstocks and products that essentially replace fossil fuel-derived products do exist, they suffer from a substantial drawback. The land area required to produce them in industrially relevant quantities is enormous. Typical yields from current agricultural production methods yield a few tonnes to tens of tonnes of biomass per hectare per year, or a conversion efficiency of solar energy to chemical energy around rather less than 1.0 %[1]. This compares with an efficiency for the best solar cells that now approaches 17%.

"Biopol" – a mixture of polyhydroxybutyrate (PHB) and valerate was developed by ICI as a biodegradeable polymer with good mechanical properties that could potentially replace oil-derived polymers, and would not suffer from the problem of polymer waste. The product was originally manufactured by fermentation, but more recent research has focussed on the possibility of producing PHB in genetically modified crops. Unfortunately its high cost has prevented it from displacing oil-derived polymers.

Drought-resistant and pollution-tolerant crops are also being developed as a way of dealing with the climate-change and pollution problems that face us.

CHALLENGES AND THE FUTURE

Environmental biotechnology has the ability to resolve significant problems in delivering a sustainable society, but it is not a panacea. For it to achieve its potential there are challenges not only for the technical community, but also for society.

TECHNICAL CHALLENGES

At a technical level, a range of challenges can be identified - modelling, development of robust

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[1] Assuming 5 tonnes carbon equivalent grown / Ha / year (Yamamoto and Yamaji 1997), this is 0.00137 kg C / m^2 / day or 0.041MJ / m^2 / day using a typical coal fuel value. Average insolation of 10-30 MJ / m^2 / day is the range of values found in the USA.

systems, extending the capabilities of biological systems, and control are significant issues.

Modelling of biological systems for design, control and optimisation is still ineffective – especially when compared with modelling capabilities in, say, the petrochemicals sector. Better modelling would enable the use of designs that were less conservative, reducing costs and/or improving performance. This problem is not just a symptom of underinvestment; it relates to the inherent difficulty of biological modelling The traditional kinetic modelling approaches are flawed in several ways.

- The models used do not fully represent the underlying biochemical mechanisms, and thus could not be expected to give reliable predictions;
- Organisms are capable of adapting to conditions – in effect changing the rate constants in models;
- The interaction between communities of organisms are complex and important, but usually ignored.

Equally, it is evident that the inherent complexity of biological systems makes their detailed modelling almost unachievable.

What is needed here is new thinking. One interesting strand of thought comes from the area of metabolic pathway engineering. Here, the models are taken back to the individual metabolic steps. By modelling the biological process in this way, researchers have sought to identify "rate limiting" transformations. Perhaps the most important issue is to understand what outcome we require from a model. The search for best "point" predictions – the traditional goal of mathematical modelling – may simply not be achievable, and we need to revise our aims.

Robustness is an issue than must be addressed – both to improve the reputation of biological techniques for effluent treatment and to deliver better performance. This can be linked to instrumentation issues – for example detecting and diverting potentially lethal doses of influent away from a biological treatment. The use of combined treatments – analogues of the membrane bioreactor, also present a way forward.

Low-waste biotechnology will become an increasing focus. The co–products of biotechnology and the effluents arising from the extraction of desired products will be under increasing scrutiny, as well as giving rise to additional cost. The "industrial ecology" concept may be useful here – designing integrated industrial systems that mimic ecosystems by using the waste from one process as the feed for another. A simple possibility might use anaerobic digestion of the waste from one process to provide the fuel to drive both.

SOCIO-ECONOMIC CHALLENGES

- Acceptance that there is a problem (short term vs long term, science vs experience)
- Acceptability
- Cost vs other technologies (typically 10s to 100s p / tonne for wastewater) – so in effluent treatment only niche applications will give high value – remediation costs ex pritchard
- Waste generation / industrial ecology

The current "industrial society" uses high-energy, high-temperature processing of minerals and metals to produce the goods that society demands. Inevitably, this generates environmental problems that are very difficult to deal with biologically. The reliance of current economic paradigms on economies of scale means that effluent and waste generation tends to occur in high quantities and in a very localised way – just the sort of wastes that are difficult to treat biologically without very large land areas.

In order for biotechnology to be more useful, other independent changes need to occur. For example, reduced reliance by society on highly toxic materials would mean that a greater proportion of wastes could be treated biologically. A shift towards distributed generation and treatment of wastes would also be useful.

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