1

Introduction to Environmental Biotechnology

The Organisation for Economic Co-operation and Development (OECD) defines biotechnology as 'the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services' (OECD, 2002). Despite the inclusiveness of this definition, there was a time when the biotechnology sector was seen as largely medical or pharmaceutical in nature, particularly amongst the general public. While to some extent the huge research budgets of the drug companies and the widespread familiarity of their products made this viewpoint understandable, it somewhat unfairly distorted the picture. Thus therapeutic instruments were left forming the 'acceptable' face of biotechnology, while elsewhere, the science was all too frequently linked with an uneasy feeling of unnatural interference. The agricultural, industrial and environmental applications of biotechnology are potentially enormous, but the shadow of Frankenstein has often been cast across them. Genetic engineering may be relatively commonplace in pharmaceutical thinking and yet when its wider use is mooted in other spheres, such as agriculture, for example even today much of society views the possibility with suspicion, if not outright hostility.

The history of human achievement has always been episodic. For a while, one particular field of endeavour seems to hold sway as the preserve of genius and development, before the focus shifts and the next wave of progress forges ahead in a dizzy exponential rush in some entirely new direction. So it was with art in the Renaissance, music in the eighteenth century, engineering in the nineteenth and physics in the twentieth. Now it is the age of the biological – in many ways forming a kind of rebirth, following on from the heyday of the great Victorian naturalists, who provided so much input into the developing science.

It is then, perhaps, no surprise that the European Federation of Biotechnology begins its 'Brief History' of the science in the year 1859, with the publication of *On the Origin of Species by Means of Natural Selection* by Charles Darwin. Though his famous voyage aboard *HMS Beagle*, which led directly to the formulation of his (then) revolutionary ideas, took place when he was a young man, he had delayed making them known until 1858, when he made a joint

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presentation before the Linnaean Society with Alfred Russell Wallace, who had, himself, independently come to very similar conclusions. Their contribution was to view evolution as the driving force of life, with successive selective pressures over time endowing living beings with optimised characteristics for survival. Neo-Darwinian thought sees the interplay of mutation and natural selection as fundamental. The irony is that Darwin himself rejected mutation as too deleterious to be of value, seeing such organisms, in the language of the times, as 'sports' – oddities of no species benefit. Indeed, there is considerable evidence to suggest that he seems to have espoused a more Lamarckist view of biological progression, in which physical changes in an organism's lifetime were thought to shape future generations.

Darwin died in 1882. Ninety-nine years later, the first patent for a genetically modified organism was granted to Ananda Chakrabarty of the US General Electric, relating to a strain of *Pseudomonas aeruginosa* engineered to express the genes for certain enzymes in order to metabolise crude oil. Twenty years on from that, the first working draft of the human genome sequence was published and the full genetic blueprint of the fruit fly, *Drosophila melanogaster*, that archetype of eukaryotic genetics research, announced – and developments have continued on what sometimes feels like an almost daily basis since then. Today biotechnology has blossomed into a major growth industry with increasing numbers of companies listed on the world's stock exchanges and environmental biotechnology is coming firmly into its own alongside a raft of 'clean technologies' working towards ensuring the sustainable future of our species and our planet.

Thus, at the other end of the biotech timeline, a century and a half on from *Origin of Species*, the principles it first set out remain of direct relevance, although increasingly in ways that Darwin himself could not possibly have foreseen.

The Role of Environmental Biotechnology

If pharmaceutical biotechnology represents the glamorous end of the market, then environmental applications are decidedly more in the Cinderella mould. The reasons for this are fairly obvious. The prospect of a cure for the many diseases and conditions currently promised by gene therapy and other biotech-oriented medical miracles can potentially touch us all. Our lives may, quite literally, be changed. Environmental biotechnology, by contrast, deals with far less apparently dramatic topics and, though their importance, albeit different, may be every bit as great, their direct relevance is far less readily appreciated by the bulk of the population. Cleaning up contamination and dealing rationally with wastes is, of course, in everybody's best interests, but for most people, this is simply addressing a problem which they would rather had not existed in the first place. Even for industry, though the benefits may be noticeable on the balance sheet, the likes of effluent treatment or pollution control are more of an inevitable obligation than a primary goal in themselves. In general, such activities are typically funded on a distinctly limited budget and have traditionally been viewed as a necessary inconvenience. This is in no way intended to be disparaging to industry; it simply represents commercial reality.

In many respects, there is a logical fit between this thinking and the aims of environmental biotechnology. For all the media circus surrounding the grand questions of our age, it is easy to forget that not all forms of biotechnology involve xenotransplantation, genetic modification, the use of stem cells or cloning. Some of the potentially most beneficial uses of biological engineering, and which may touch the lives of the majority of people, however indirectly, involve much simpler approaches. Less radical and showy, certainly, but powerful tools, just the same. Environmental biotechnology is fundamentally rooted in waste, in its various guises, typically being concerned with the remediation of contamination caused by previous use, the impact reduction of current activity or the control of pollution. Thus, the principal aims of this field are the manufacture of products in environmentally harmonious ways, which allow for the minimisation of harmful solids, liquids or gaseous outputs or the clean-up of the residual effects of earlier human occupation.

The means by which this may be achieved are essentially twofold. Environmental biotechnologists may enhance or optimise conditions for existing biological systems to make their activities happen faster or more efficiently, or they resort to some form of alteration to bring about the desired outcome. The variety of organisms which may play a part in environmental applications of biotechnology is huge, ranging from microbes through to trees and all are utilised on one of the same three fundamental bases – accept, acclimatise or alter. For the vast majority of cases, it is the former approach, accepting and making use of existing species in their natural, unmodified form, which predominates.

The Scope for Use

There are three key points for environmental biotechnology interventions, namely in the manufacturing process, waste management or pollution control, as shown in Figure 1.1.

Accordingly, the range of businesses to which environmental biotechnology has potential relevance is almost limitless. One area where this is most apparent

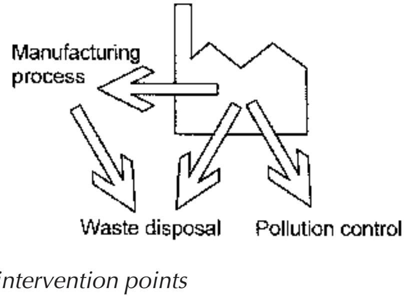

Figure 1.1 *The three intervention points*

is with regard to waste. All commercial operations generate waste of one form or another and for many, a proportion of what is produced is biodegradable. With disposal costs rising steadily across the world, dealing with refuse constitutes an increasingly high contribution to overheads. Thus, there is a clear incentive for all businesses to identify potentially cost-cutting approaches to waste and employ them where possible. Changes in legislation throughout Europe, the US and elsewhere, combined with growing environmental awareness and a burgeoning demand for reduced carbon footprints have inevitably driven these issues higher up the political agenda and biological methods of waste treatment have gained far greater acceptance as a result. For those industries with particularly high biowaste production, the various available treatment biotechnologies can offer considerable savings.

Manufacturing industries can benefit from the applications of whole organisms or isolated bio-components. Compared with conventional chemical processes, microbes and enzymes typically function at lower temperatures and pressures. The lower energy demands this makes leads to reduced costs, but also has clear benefits in terms of both the environment and work-place safety. Additionally, biotechnology can be of further commercial significance by converting low cost organic feedstocks into high value products or, since enzymatic reactions are more highly specific than their chemical counterparts, by deriving final substances of high relative purity. Almost inevitably, manufacturing companies produce wastewaters or effluents, many of which contain biodegradable contaminants, in varying degrees. Though traditional permitted discharges to sewer or watercourses may be adequate for some, other industries, particularly those with recalcitrant or highly concentrated effluents, have found significant benefits to be gained from using biological treatment methods themselves on site. Though careful monitoring and process control are essential, biotechnology stands as a particularly cost-effective means of reducing the pollution potential of wastewater, leading to enhanced public relations, compliance with environmental legislation and quantifiable cost-savings to the business.

Those involved in processing organic matter, for example or with drying, printing, painting or coating processes, may give rise to the release of volatile organic compounds (VOCs) or odours, both of which represent environmental nuisances, though the former is more damaging than the latter. For many, it is not possible to avoid producing these emissions altogether, which leaves treating them to remove the offending contaminants the only practical solution. Especially for relatively low concentrations of readily water soluble VOCs or odorous chemicals, biological technologies can offer an economic and effective alternative to conventional methods.

The use of biological cleaning agents is another area of potential benefit, especially where there is a need to remove oils and fats from process equipment, work surfaces or drains. Aside from typically reducing energy costs, this may also obviate the need for toxic or dangerous chemical agents. The pharmaceutical and brewing industries, for example both have a long history of employing enzyme-based cleaners to remove organic residues from their process equipment.

In addition, the development of effective biosensors, powerful tools which rely on biochemical reactions to detect specific substances, has brought benefits to a wide range of sectors, including the manufacturing, engineering, chemical, water, food and beverage industries. With their ability to detect even small amounts of their particular target chemicals, quickly, easily and accurately, they have been enthusiastically adopted for a variety of process monitoring applications, particularly in respect of pollution assessment and control.

Contaminated land is a growing concern for the construction industry, as it seeks to balance the need for more houses and offices with wider social and environmental goals. The re-use of former industrial sites, many of which occupy prime locations, may typically have associated planning conditions attached which demand that the land be cleaned-up as part of the development process. With urban regeneration and the reclamation of ‘brown-field’ sites increasingly favoured in many countries over the use of virgin land, remediation has come to play a significant role and the industry has an on-going interest in identifying cost-effective methods of achieving it. Historically, much of this has involved simply digging up the contaminated soil and removing it to landfill elsewhere. Bioremediation technologies provide a competitive and sustainable alternative and in many cases, the lower disturbance allows the overall scheme to make faster progress.

As the previous brief examples show, the range of those which may benefit from the application of biotechnology is lengthy and includes the chemical, pharmaceutical, water, waste management and leisure industries, as well as manufacturing, the military, energy generation, agriculture and horticulture. Clearly, then, this may have relevance to the viability of these ventures and, as was mentioned at the outset, biotechnology is an essentially commercial activity. Environmental biotechnology must compete in a world governed by the Best Practicable Environmental Option (BPEO) and the Best Available Techniques Not Entailing Excessive Cost (BATNEEC). Consequently, the economic aspect will always have a large influence on the uptake of all initiatives in environmental biotechnology and, most particularly, in the selection of methods to be used in any given situation. It is impossible to divorce this context from the decision-making process. By the same token, the sector itself has its own implications for the wider economy.

The Global Environmental Market

The global environmental market is undergoing a period of massive growth. In 2001, the UK’s Department of Trade and Industry estimated its value at around 1500 billion US dollars, of which some 15–20% was biotech-based. Although the passage of time has now shown some of the growth forecasts then made for the following years to have been somewhat optimistic, a recent study predicts that the market will have grown to 7400 billion US dollars by 2025 (Helmut Kaiser Consultancy, 2009). There are several major factors acting as drivers for this growth, including a greater general awareness of environmental issues, the widespread adoption of sustainable best practice by industry and geo-political changes that open new territories for technology transfer. In addition, biotechnology has increasingly gained acceptance for clean manufacturing applications, with the use of biomimetics in particular showing marked expansion over recent years, while energy production, waste management and land remediation have all benefited from the ongoing trend stimulating the sales of biotechnology-based environmental processing methods. Water treatment in its broadest sense has been perhaps the biggest winner in all this, the sector now accounting for some 25% of the total global environmental market (Helmut Kaiser Consultancy, 2009).

The export of environmental technologies is now a significant contributor to the global market, which will continue to expand in the burgeoning worldwide trend towards driving economic development alongside strong ecological awareness. Although such technology transfer is likely to continue to play a major role on the global scene, it is also probable that many countries will increasingly build their own comprehensive indigenous environmental industry over the coming years, thus circumventing their dependence on innovation imports.

Over the last decade, as many predicted, the regulatory framework across the world has experienced a radical tightening, with existing legislation on environmental pollution being more rigorously enforced and more stringent compliance standards implemented. It is hard to imagine that this trend will stop in the coming years, which once again feeds the expectation that it will act as a significant stimulus for the sales of biotechnology-based environmental processing methods. This would seem particularly likely in the current global main markets for environmental technologies, namely Asia in general, China, Japan, Europe and the USA (Helmut Kaiser Consultancy, 2009).

The benefits are not, however, confined to the balance sheet. The OECD (2001) concluded that the industrial use of biotechnology commonly leads to increasingly environmentally harmonious processes and additionally results in lowered operating and/or capital costs. For years, industry has appeared locked into a seemingly unbreakable cycle of growth achieved at the cost of environmental damage. This OECD investigation provided probably the first hard evidence to support the reality of biotechnology's long heralded promise of alternative production methods which are ecologically sound and economically efficient. A variety of industrial sectors, including pharmaceuticals, chemicals, textiles, food and energy were examined, with a particular emphasis on biomass renewable resources, enzymes and bio-catalysis. While such approaches may have to be used in tandem with other processes for maximum effectiveness, it seems that their use invariably leads to reduction in operating or capital costs, or both. Moreover, the research also concluded that it is clearly in the interests of governments of the developed and developing worlds alike to promote the use of biotechnology for the substantial reductions in resource and energy consumption, emissions, pollution and waste production it offers. The potential contribution to be made by the appropriate use of biotechnology to both environmental and economic sustainability would seem to be clear.

The upshot of this is that few biotech companies in the environmental sector perceive problems for their own business development models, principally as a result of the wide range of businesses for which their services are applicable and the large potential for growth. Competition within the sector is not seen as a major issue either, since the field is still largely open and unsaturated, and from the employment perspective, the biotech industry seems a robust one. Although the economic downturn saw the UK science labour market in general shed both permanent and contract staff throughout 2009, the biotech sector increased its demand for skilled scientists and predictions suggest that it will continue to buck the trend in the future (SRG, 2010). Moreover, there has been an established tendency towards niche specificity, with companies operating in more specialised sub-arenas within the environmental biotechnology umbrella. Given the number and diversity of such possible slots, coupled with the fact that new opportunities, and the technologies to capitalise on them, are developing apace, this trend seems likely to continue, though the business landscape is beginning to change. In some sectors, aggressive rivalry for market penetration has begun to produce bigger, multi-disciplinary environmental companies, largely through partnerships, acquisitions and direct competition. It is not without some irony that companies basing their commercial activities on biological organisms should themselves come to behave in such a Darwinian fashion. However, the picture is not entirely rosy.

Typically the sector comprises a number of relatively small, specialist companies. According to the *OECD Biotechnology Statistics 2009*, based on government survey data for 22 OECD countries and an additional four non-member countries, the majority of both biotechnology and biotechnology R&D companies have fewer than 50 employees – the average by country being 67 and 63% respectively (van Beuzekom and Arundel, 2009). As a consequence, the market has tended to be somewhat fragmented. Often the complexities of individual projects make the application of 'standard' off-the-shelf approaches very difficult, inevitably meaning that much of what is done must be significantly customised. While this, of course, is a strength and of great potential environmental benefit, it also has hard commercial implications which must be taken into account. Although the situation has begun to be addressed over recent years, historically a sizeable proportion of companies active in this sphere have had few products or services which might reasonably be termed suitable for generalised use, though they may have enough expertise, experience or sufficiently perfected techniques to deal with a large number of possible scenarios.

Historically, one of the major barriers to the wider uptake of biological approaches has been the high perceived cost of these applications. For many years, the solutions to all environmental problems were seen as expensive and for some, particularly those unfamiliar with the multiplicity of varied technologies available, this view has been slow to fade. Generally, there is often a lack of financial resource allocation available for this kind of work and biotech providers have sometimes come under pressure to reduce the prices for their services as a result. Awareness of the benefits of biotechnology, both as a means to boost existing markets and for the opening up of new ones, has undoubtedly been growing over the last ten years but it remains an important area to be addressed. The lack of marketing expertise that had formed one of the principal obstacles to the exploitation of novel opportunities, particularly in the UK, has been largely overcome, while in addition, technical understanding of biotech approaches amongst many target industries has also risen. Good education, in the widest sense, of customers and potential users of biological solutions will remain a major factor in the development and furtherance of these technologies.

Modalities and local influences

Another of the key factors affecting the practical uptake of environmental biotechnology is the effect of local circumstances. Contextual sensitivity is almost certainly the single most important factor in technology selection and represents a major influence on the likely penetration of biotech processes into the market place. Neither the nature of the biological system, nor of the application method itself, play anything like so relevant a role. This may seem somewhat unexpected at first sight, but the reasons for it are obvious on further inspection. While the character of both the specific organisms and the engineering remain essentially the same irrespective of location, external modalities of economics, legislation and custom vary on exactly this basis. Accordingly, what may make abundant sense as a biotech intervention in one region or country, may be totally unsuited to use in another. In as much as it is impossible to discount the wider global economic aspects in the discussion, disassociating political, fiscal and social conditions equally cannot be done, as the following example illustrates. Back in 1994, the expense of bioremediating contaminated soil in the United Kingdom greatly exceeded the cost of removing it to landfill. Within six years successive changes of legislation and the imposition of a landfill tax, the situation was almost completely reversed. Unsurprisingly, in those countries where landfill had always been an expensive option and thus played less of a major role in national waste management strategy, remediation has generally tended to be embraced far more readily.

While it is inevitable that environmental biotechnology must be considered as contextually dependent, clearly as the previous example shows, those contexts can change. In the final analysis, it is often fiscal instruments, rather than the technologies, which provide the driving force and sometimes seemingly minor modifications in apparently unrelated sectors can have major ramifications for the application of biotechnology. Again as has been discussed, the legal framework is another aspect of undeniable importance in this respect. Increasingly tough environmental law makes a significant contribution to the sector and changes in regulatory legislation are often enormously influential in boosting existing markets or creating new ones. When legislation and economic pressure combine, as, for example they have with the likes of European Directives on Landfill, Integrated Pollution Control and Urban Wastewater, the impetus towards a fundamental paradigm shift becomes overwhelming and the implications for relevant biological applications can be immense.

There is a natural tendency to delineate, seeking to characterise technologies into particular categories or divisions. However, the essence of environmental biotechnology is such that there are many more similarities than differences. Though it is, of course, often helpful to view individual technology uses as distinct, particularly when considering treatment options for a given environmental problem, there are inevitably recurrent themes which feature throughout the whole topic. Moreover, this is a truly applied science. While the importance of the laboratory bench cannot be denied, the controlled world of research translates imperfectly into the harsh realities of commercial implementation. Thus, there can often be a dichotomy between theory and application and it is precisely this fertile ground which is explored in the present work. In addition, the principal underlying approach of specifically *environmental* biotechnology, as distinct from other kinds, is the reliance on existing natural cycles, often directly and in an entirely unmodified form. Thus, this science stands on a foundation of fundamental biology and biochemistry. To understand the application, the biotechnologist must simply examine the essential elements of life, living systems and ecological circulation sequences. However engineered the approach, this fact remains unwaveringly true. In many respects, environmental biotechnology stands as the purest example of the multi-faceted bio-industry, since it is the least refined, at least in terms of the basis of its action. In essence, all of its applications simply encourage the natural propensity of the organisms involved, while seeking to enhance or accelerate their action. Hence, optimisation, rather than modification, is the typical route by which the particular desired end result, whatever it may be, is achieved and, consequently, a number of issues feature as common threads within the discussions of individual technologies.

Integrated Approach

Integration is an important aspect for environmental biotechnology. One theme that will be developed throughout this book is the potential for different biological approaches to be combined within treatment trains, thereby producing an overall effect which would be impossible for any single technology alone to achieve. However, the wider goal of integration is not, of necessity, confined solely to the specific methods used. It applies equally to the underpinning knowledge that enables them to function in the first place and an understanding of this is central to the rationale behind this book. In some spheres, traditional biology has become rather unfashionable and the emphasis has shifted to more exciting sounding aspects of life science. While the new-found concentration on 'ecological processes', or whatever, sounds distinctly more 'environmental', in many ways, and somewhat paradoxically, it sometimes serves the needs of environmental biotechnology rather less well. The fundamentals of living systems are the stuff of this branch of science and complex though the whole picture may be, at its simplest the environmental biotechnologist is principally concerned with a relatively small number of basic cycles. In this respect, a good working knowledge of biological processes like respiration, fermentation and photosynthesis, a grasp of the major cycles by which carbon, nitrogen and water are recycled and an appreciation of the flow of energy through the biosphere must be viewed as prerequisites. Unsurprisingly, then, these basic processes appear throughout this book, either explicitly or tacitly accepted as underpinning the context of the discussion. The intent here has been neither to insult the readership by parading what is already well known, nor gloss over aspects which, if left unexplained, at least in reasonable detail, might only serve to confuse. However, this is expressly not designed to be a substitute for much more specific texts on these subjects, nor an entire alternative to a cohesive course on biology or biochemistry. The intention is to introduce and explain the necessary aspects and elements of various metabolic pathways, reactions and abilities as required to advance the reader's understanding of this particular branch of biotechnology.

A large part of the reasons for approaching the subject in this way is the fact that there really is no such thing as a 'typical' environmental biotechnologist any more than there is a 'typical' environmental science student. The qualifications, knowledge base and experience of each means that practitioners come into the profession from a wide variety of disciplines and by many different routes. Thus, amongst their ranks are agronomists, biochemists, biologists, botanists, enzymologists, geneticists, microbiologists, molecular biologists, process engineers and protein technologists, all of whom bring their own particular skills, knowledge base and experiences. The applied nature of environmental biotechnology is obvious. While the science underlying the processes themselves may be as pure as any other, what distinguishes this branch of biological technology are the distinctly real-life purposes to which it is put. Hence, part of the intended function of this book is to attempt to elucidate the former in order to establish the basis of the latter. At the same time, as any applied scientist will confirm, what happens in the field under operational conditions represents a distinct compromise between the theoretical and the practically achievable. At times, anything more than an approximation to the expected results may be counted as something of a triumph of environmental engineering.

Closing Remarks

The celebrated astronomer and biologist, Sir Fred Hoyle, said that the solutions to major unresolved problems should be sought by the exploration of radical hypotheses, while simultaneously adhering to well tried and tested scientific tools and methods. This approach is particularly valid for environmental biotechnology. With new developments in treatment technologies appearing all the time, the list of what can be processed or remediated by biological means is ever changing. By the same token, the applications for which biotechnological solutions are sought are also subject to alteration. For the biotech sector to keep abreast of these new demands it may be necessary to examine some truly 'radical hypotheses' and possibly make use of organisms or their derivatives in ways previously unimagined. This is the basis of innovation; the inventiveness of an industry is often a good measure of its adaptability and commercial robustness.

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