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COMMENTARY

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The industrial sustainability of bioremediation processes

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Population growth and global industrialization have placed major pressures on our environment, potentially threatening its sustainability. This has resulted in the build-up of chemical contaminants throughout the biosphere, especially in soils and sediments. Annual amounts of individual bulk chemicals produced in the United States range from 5 to 20 million metric tons for ethylene, propylene, vinyl chloride, benzene, and ethylbenzene and 1–5 million tons for a large number of other organic chemicals. Approximately 140 million ton per annum of synthetic polymers/plastics are produced globally [7]. If only 1% of world crude oil entered the environment through spills, waste disposal or volatilization, this amounts to 266 million barrels per annum.

Many chemicals that have been synthesized in high volumes differ substantially in structure from natural organic compounds and are often recalcitrant to biodegradation. Other compounds, such as the polycyclic aromatic hydrocarbons (PAHs), the toxic and carcinogenic products of incomplete combustion of natural organic compounds and hydrocarbons, contaminate soil or industrial sites as a result of naturally ignited forest fires or when generated as wastes or by-products of industrial processes. PAHs, having four or more fused rings, are typically recalcitrant to biodegradation. Industrial activities have also resulted in undesired contamination of soil and other media with heavy metals that are often toxic to human and animal health. While many microbes can transform metals from toxic to non-toxic species or alter their solubility or availability [2], the biotechnology to remediate these contaminants is more complex and arguably less advanced.

High-profile cases of environmental chemical contamination have emerged. For example, 22,000 tons of PCBc, dioxins, pesticides, and other chemical wastes were disposed of in the Love Canal area in Niagara Falls, New York, during the 1940s and early 1950s. When the site was later covered up and used as a location for a school and housing, high rates of miscarriages and birth abnormalities were encountered among residents. The Love Canal disaster led to the establishment of the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), which, together with later Superfund initiatives, provided a basis for regulating the disposal of hazardous waste and the clean-up of contaminated sites in the United States. Remediation of the Exxon Valdez oil spill off the coast of Alaska demonstrated the potential for large-scale application of bioremediation processes for cleaning contaminated water and soil.

While microbiology has been the clear driver of the technology, bioremediation is interdisciplinary, also involving engineering, geology, ecology, and chemistry. A variety of approaches to soil bioremediation have been developed and implemented, ranging from in-situ subsurface (unexcavated) processes, to land-farming and engineered soil pile approaches, to use of completely mixed-soil slurry reactor systems for treatment of excavated soils. The common objective in the various processes is to create the necessary environment to facilitate growth and contaminant degradation by the appropriate biological organisms. Bioremediation has now been used successfully to remediate sites contaminated with hydrocarbons or other selected contaminants and has been the preferred process for clean-up of contamination around leaking underground storage tanks in the US [3]. Most common non-biological approaches are land-filling, soil vapor extraction, thermal desorbtion, incineration, and soil washing.

The following advantages are often cited for use of bioremediation approaches:

1. They are generally the least expensive remediation alternatives [1].
2. The processes are flexible and adaptable to variable environmental conditions and, over time, microor-

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ganisms evolve that can degrade novel synthetic chemical structures [5].

3. The processes are perceived as being environmentally benign whereas incineration and more energy- and equipment-intensive processes are perceived as being more polluting.
4. The processes are implementable on site, indeed often in situ, and with dilute or widely diffused contaminants [4].

On the negative side, there have also been many instances in which bioremediation failed to reduce contaminant levels to defined concentration criteria, and processes are also often criticized as being too slow. Consumers have been reluctant to use bioremediation technology because of its history of failures due to the presentation of "quick-fix" technologies [8]. This may explain why bioremediation currently represents only a small portion of the US$7–8 billion annual U.S. remediation market. There can be many reasons for slow bioremediation rates and failures; principally, that the environmental conditions present are suboptimal for selection and growth promotion of the degrading strains. In addition, the kinetics of microbial growth and biodegradation are such that, as contaminant concentrations decline, so also do the rates of their further degradation.

Factors affecting the key rates and extents of contaminant degradation relate to the nature of the contaminant(s) (structure, water solubility, bioavailability, biodegradability, cometabolism potential, substrate/metabolite concentration, and toxicity), the properties of the soil and the nature of the process (homo- or heterogeneous environment; contents of water, nutrients, and oxygen; presence of bioavailability enhancing agents), temperature, pH and, the size and make-up of the microbial population. Bioremediation processes having more limited microbial intervention tend to be more prolonged and unreliable. Where the process environment is non-homogeneous, sampling and analytical costs are substantially increased and may become the dominant cost component in the project. Increased microbial technology intervention can lead to more accelerated processes, greater process reliability, and lower end-points [12].

The durations of processes may range from 5 to 25 years for natural attenuation processes, 0.5–3 years for in-situ subsurface processes, 1–18 months for soil pile/composting processes, 1–12 months for land-farming and slurry phase systems, and 15 days for accelerated slurry phase systems [11]. Average daily rates of contaminant degradation can range from 5 ppm to 10,000 ppm for natural attenuation processes to accelerated slurry phase systems.

With a diverse mixture of contaminants, as is present in oil spills, there is also evidence that prolonged bioremediation processes are typically disadvantageous, because significant amounts of contaminants may be removed by non-biological mechanisms and the extents of contaminant degradation achieved are often not adequate. Thus, in prolonged bioremediation processes the early loss of volatiles and/or the metabolism of low-molecular-weight compounds can reduce the bioavailability and cometabolic biodegradation potential of high-molecular-weight compounds. The resultant removal of the carbon and energy for microbial growth will lead to a decline in the hydrocarbon-degrading and general microbial population.

Many authors have provided guidance for determining the suitability of bioremediation as a clean-up option and questions to be addressed related to the nature of the contaminants: the impact of how long the site has been contaminated on removal of the easier-to-degrade compounds such that the more-difficult-to-degrade compounds may still require remediation; the ability of known microbial systems and/or the microbial population at the site to degrade the contaminants; factors limiting population growth and contaminant degradation; the potential to remove metals by phytoremediation or to reduce toxicities of metals by alterations in physical or chemical state and the potential to achieve clean-up criteria. With regard to selection of bioremediation configuration for treatment of different classes of chemicals, natural attenuation and electron donor delivery were considered to be options for treatment of chlorinated solvents, while biostimulation was an option for remediation of chlorinated solvents and phenols [3]. Bioventing was an option for treating PAHs. Land treatment or composting were options for nitroaromatics, phenols, and PAHs; and bioslurry processes represented a treatment option for all of the above-mentioned chemicals. All treatment methods, except electron-donor delivery, were potential approaches to monoaromatic hydrocarbon bioremediation. While all of this guidance is instructive, one cannot help getting the impression that there are a lot of barriers or pitfalls to be aware of when embarking on a bioremediation project—just how reliable or robust is the technology?

In the early 1990s, the perceived advantages of bioremediation processes resulted in significant research and commercial interest in bioremediation technologies, and investors, technologists, and entrepreneurs responded through creation of a substantial number of bioremediation companies whose missions were to develop and implement bioremediation technologies. Suffice it to say that these companies struggled at best and few have survived by sticking to their original missions.

So, given that soil remediation opportunities exist widely, why have we not seen the development of a strong bioremediation-based industrial sector? One dimension of the problem is that bioremediation processes are perceived to be project-specific, requiring a lot of customization, which does not endear the technology to investors, who like more widely distributable technology. Case-by-case customization and technology implementation failures have retarded development of environmental biotechnology enterprises, and more rigorous approaches to technology selection and its strategic development and commercialization are required.

We need to develop more robust/versatile processes that do not require research and development for each project. Wider use of more controlled reactor-based accelerated bioremediation processes ought to be considered. The market, legislative decisions, and government funding initiatives all appear to favor pursuit of enhanced bioremediation approaches. Much of the activity in bioremediation technology is at the research and development level, and there is a need to develop strategies to successfully convert more of the new research findings into reliable processes. We need to accept that a biological solution may not always be the most cost-effective one. As we look to the future, the focus of bioremediation will shift from clean-up of spills or sites contaminated prior to the regulatory era of recent years to the remediation of accidental spills, the treatment/recycling of high-volume wastes, and applying the best available biological methods to addressing these problems.

In addition to chemical wastes, biological wastes and contaminants represent a second category of waste that seriously threatens the environment, including sewage sludge (biosolids), animal and fowl manures, and rendering plant wastes. While these wastes have traditionally been recycled into soil or placed in landfill, increased urbanization and intensification of farming and food practices is making these disposal methods impractical. In addition concerns regarding transmission of infectious diseases, such as BSE, foot and mouth, West Nile and those caused by intestinal bacterial pathogens have recently been highlighted. Infected waste materials applied to soil have the potential for disease spread through direct or indirect contact with watercourses, plants, animals, or humans. The potential introduction to or disposal of recombinant organisms in soil represents a new but related concern. Alternative economical and safe waste disposal approaches are urgently needed for these biological wastes.

Prince [6] defined bioremediation as "the process of judiciously exploiting biological processes to minimize an unwanted environmental impact; usually it is the removal of a contaminant from the biosphere", although other definitions also exist. Thus, bioremediation should be viewed in this broader context (not just for soil), with enormous opportunities to apply microbial expertise to develop and improve methods for treating oily sludges, human, animal, vegetable/food processing wastes, high concentration organic liquid wastes and air streams. The remediation services market represents less than 4% of the 213 billion dollar annual environmental industry market, which supports the case for expanding the horizons of bioremediation [8].

Environmental bioprocesses must comply with good commercial-process operating principles of having high throughputs, low batch-to-batch variation, predictable end-points, and controllable costs leading to acceptable profit margins. Bioremediation processes have often been implemented without the assurance of a positive outcome or by unskilled personnel, leading to a high risk of failure. Processes must be validated such that they do not fail and they must be implemented by competent personnel and withstand the same technoeconomic rigor on which all commercially viable processes rely. All relevant factors must be considered, including waste/contaminated material supply continuity, process end-products/uses, transport costs, all process costs, potential technology advances, environmental impacts, and health and safety. These criteria also need to be applied at the research and development investment stage in order to identify and qualify potential target processes. Intellectual-property protection is essential to having a competitive advantage where widespread process distribution is desired, especially recognizing that secrecy is difficult to maintain in environmental processes, which may operate in open areas or where regulatory permits may require the making of process details public.

As in other fields of biotechnology, we industrial microbiologists must recognize that healthy competition exists between biological, chemical, and physical approaches, and the potential for developments in any of these fields as well as external factors will shift the balance in competition. For example, chemically produced industrial ethanol production was practiced in the late 1800s. A fermentation approach dominated in the 1940s but this was somewhat displaced by efficient ethylene hydration processes in the 1950s and 1960s, when ethylene was cheap. In turn, as a result of the 1973 oil embargo, oil and ethylene prices rose dramatically and fermentation routes became dominant again [10]. Appropriate commercial risk assessments are needed to evaluate long-term competitiveness of specific bioremediation processes vis-à-vis alternative non-biological treatment options. For applied microbiologists, who are rightly so passionate about the current status and future potential of our discipline, implementation of such a dispassionate evaluation process understandably 'goes against the grain', but it surely adds to the credibility of our discipline.

Bioremediation research has also captivated the imaginations of many young talented undergraduate and graduate students who would like to pursue careers in this area. Most of the career opportunities to date appear to be in university and government institutes, rather than in industry. Through our research we need to enhance the reliability of bioremediation processes, as well as to expand the industrial dimension in order to create more solid careers for young industrial microbiologists. Surely the emerging scientific base for environmental biotechnology is strong enough to provide a resilient industrial technology with its associated industrial career opportunities.

A recent review places environmental biotechnology in a somewhat embarrassing light, suggesting that, although microorganisms have the primary catalytic role in bioremediation, our knowledge of the alterations occurring in the microbial communities remains limited 'and the microbial community is still treated as a "black box" ' [4]. Perhaps the implied criticism is deserved. However, the much more precise perspective we are gaining of individual microbial species and even of mixed microbial populations as they exist in the environment, as a result of the development of advanced molecular techniques and genomics, will insure a bright future for bioremediation technology [9]. Nonetheless, in our excitement to apply this new knowledge, we industrial microbiologists need to make sure that we do not ignore well-proven technical and economic processing principles. After all, these standards have served us well with established microbial technology (for example, fermentation processes) for many decades.

References

1. Grommen R, Verstraete W (2002) Environmental biotechnology: the ongoing quest. J Biotechnol 98:113–123
2. Harayama, S (2001) Environmental biotechnology. Curr Opin Biotechnol 12:229–230
3. Hughes JB, Neale CN, Ward CH (2000) Bioremediation. Enclyclopedia of microbiology, 2nd edn. Academic, New York, 587–610
4. Iwamoto T, Nasu M (2001) Current bioremediation practice and perspective. J Biosci Bioeng 92:1–8
5. Mandelbaum RT, Allan DL, Wackett LP (1995)Isolation and characterization of a *Pseudomonas* sp that mineralizes the s-triazine herbicide atrazine. Appl Environ Microbiol 61:1451–1457
6. Prince RC (1998) Bioremediation. In: Kirk-Othmer encyclopedia of chemical technology. Supplement to the 4th edn. Wiley, New York, pp 48–89
7. Shimao M (2001) Biodegradation of plastics. Curr Opin Biotechnol 12:242–247
8. Srinivasan U. (2003) U.S. bioremediation markets. Frost and Sullivan research report, no. 7857. Frost and Sullivan, Palo Alto, California, pp 1–300
9. VanHamme J, Singh A, Ward OP (2003) Recent advances in petroleum microbiology. Microbiology and Molecular Biology Reviews 67:503–549
10. Ward OP (1989) Fermentation biotechnology, principles, processes and products. Prentice Hall, Englewood, New Jersey
11. Ward OP, Singh A (2004) Evaluation of current soil bioremediation technologies. In: Singh A, and Ward OP (eds) Applied bioremediation and phytoremediation. Soil biology series, vol 1. Springer, Berlin Heidelberg New York (in press)
12. Ward OP, Singh A, VanHamme J (2003) Accelerated bioremediation of petroleum hydrocarbon waste. J Ind Microbiol Biotechnol 30:260–270