Sustainable development: how can biotechnology contribute?

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Sustainable development has become a priority for the world's policy makers. Among the broad range of technologies with the potential to reach the goal of sustainability, biotechnology could take an important place, especially in the fields of food production, renewable raw materials and energy, pollution prevention, and bioremediation. However, technical and economic problems still need to be solved. In some cases, the environmental impact of biotechnological applications has been misjudged; in other cases, expectations cannot yet be matched.

The dispute over humanity's impact on the environment has come of age. Our destructive activities can no longer be denied, but we also depend crucially on the continuation of our economic activities. Hence, a compromise has to be worked out: sustainable development.

The concept of sustainable development was launched by the World Commission on Environment and Development in the report *Our common future* in 1987 and reinforced by the UN Earth Summit in Rio de Janeiro in 1992. Its outcome can be summarized as follows: recognizing a return to a natural lifestyle as impossible, there is no option but to try to run the human-controlled space (noosphere) in the way good managers would run a company if intending to pass it on to their children.

The problems in realizing this goal are tremendous: The volume of expenditure necessary to remedy environmental problems in the countries of the European Union during the 1990s has been estimated at £200 billion for waste management, £100 billion to ensure water quality and £237 billion to counterbalance the greenhouse effect[1]; the figures for the USA are £170 billion, £71 billion and £443 billion, respectively[1]. The Worldwatch Institute, using a completely different approach, estimated the cost of achieving sustainable development up to the year 2000 at over US$700 billion, including the protection of topsoil on cropland (US$114 billion), reforestation (US$32 billion), slowing the rates of population growth (US$155 billion), raising energy efficiency (US$180 billion) and developing renewable energy sources (US$94 billion)[2].

How can sustainable development be achieved?

Already, a whole range of technologies has been developed or adapted, including renewable energies, new materials, environment-friendly chemicals, transport and processing systems, and adequate monitoring and control methods. The various technologies summarized under 'biotechnology' could play a major role in most of these fields but will they, in all situations, be efficient and effective enough to justify the necessary investment? A critical evaluation of current approaches and results is needed in order to determine this.

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This article will review the opportunities and problems involved in the application of biotechnology to sustainable development. It will not present an overview of the concept of sustainability, nor discuss non-technical aspects. Even the debate about potential risks, and therefore public acceptance, of certain biotechnological applications cannot be presented here for lack of space. Four fields have been selected in which biotechnological applications might have a major impact: food production, renewable materials, waste prevention and bioremediation.

Food production

Considering the rapidly growing world population and the detrimental impact of agricultural systems on the environment, we need to develop a sustainable form of food production. The challenges are considerable[3]: approximately 42% of crop productivity is lost to competition with weeds and to pests and pathogens, and crop varieties are nearing their biological and physical limits of productivity. There are several potential key contributions of biotechnology to remedy this situation.

- Producing more food on the same area of land, reducing pressure to expand into the wilderness, rain forests and marginal lands, which support biodiversity and vital ecosystems.
- Reducing post-harvest losses and improving the quality of fresh and processed foods, thus boosting the realized nutritional yield per acre.
- Displacing resource- and energy-intensive inputs, such as fuel, fertilizers or pesticides, thus reducing unintended impacts on the environment and freeing those resources to be used for other purposes or to be conserved for the future.
- Encouraging the reduction of environmentally damaging agricultural practices and the adoption of sustainable practices such as conservation tillage, precision agriculture and integrated crop managements[4].

Resources

The most essential resources for food production are water, soil and energy. Biotreatment and bioremediation techniques are useful tools to control water quality, monitor pollution, decontaminate waste waters and prevent pollution (see the Bioremediation section below). Soil is vulnerable to inappropriate management practices:

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natural and man-made factors contribute to an annual loss of approximately 1.4% of the total top soil[3].

In regions lacking water, plant biotechnology could help to develop crop plants with inherent resistance to drought or salt[5]; modern plant-breeding and -engineering techniques could help in selecting and developing plant varieties better adapted to a whole range of stress factors, including heat and cold as well as drought and salt[6–8]. A special challenge is to develop plants that do not exhaust the soil fertility. In some cases, molecular- or cellular-engineering methods will help to create optimally adapted varieties, such as non-leguminous crops that are able to take up nitrogen or phosphorus.

Fertilizers

Alternatives to agrochemicals (such as synthetic fertilizers, herbicides and pesticides) are important in order to maintain a certain ecological stability. Potential alternatives to chemical fertilizers include fermentation sludge, chitosan (from crustaceans) and cyanobacteria (already tested in rice paddies[9]). The prospects for such biological fertilizers are very promising. For example, Kenya is producing BIOFIX, a rhizobium inoculant, 100 g of which costs about US$1.25 and fertilizes 1 hectare of beans; this replaces 90 kg of chemical nitrogen that costs approximately ten times more[10]. The inoculation of rice with mycorrhizal fungi and *Alcaligenes faecalis* demonstrated that nitrogen fixation rates could be increased by 15–20% and rice yields by 5–12%[11,12]. Nitrogen-fixing plants represent another way to replace chemicals but the transformation of the major crop plants with nitrogen-fixation genes from rhizobia has not yet been successful[13].

Herbicides

Herbicide-tolerant crops have been developed to reduce herbicide use, especially by applying herbicides early in the growing season; in 1998, 19.8 million hectares of herbicide-resistant crops were planted worldwide (excluding China). This has often been presented as a significant example of applying biotechnology in a non-sustainable way. Critics expect that even a low-level application of herbicides might be able to promote herbicide resistance in weeds[14].

In fact, genes conferring resistance to herbicides already exist in many wild plants, because herbicidal substances have been produced by some plants to block their competitors' growth[14]. Hence, massive herbicide use is likely to build up a selection pressure enabling the resistance genes to spread throughout the plant population[15]. The risk of horizontal gene spreading will demand the use of alternative herbicides and the subsequent development of additional resistant crop plants but will not have any major impact on the environment. Agrobiotechnology companies such as Monsanto and Novartis have recognized the problem and developed programmes to prevent resistance build-up.

Pesticides

Pesticide use is often considered to be detrimental to sustainable development, because the inevitable increase in resistance requires continually higher doses and can lead to the extinction of useful predators. A whole range of alternative solutions to control plant pests are available:

- natural predators (such as wasps) and pathogens (bacteria, viruses, fungi);
- biopesticides based on plant products (e.g. pyrethrum);
- insect-derived semiochemicals, such as sex and alarm pheromones, neuropeptides and repellents[16].

Although specially bred wasps are widely used to reduce the number of plant-feeding insects[16], only a few products based on bacteria, viruses or fungi are yet close to the market place. Organic bioinsecticides, such as plant-derived biopesticides, pheromones and repellents, have a number of advantages, including the fact that they are species specific and biodegradable. Unfortunately, high specificity usually means a limited range of applications and a smaller market size, while rapid degradability means repeated applications, hence higher costs.

The engineering of insecticidal genes from *Bacillus thuringiensis* (Bt) into crop plants has been carried out on a large scale. In 1998, 22% of the area planted with maize in the USA (~6.5 million hectares) consisted of Bt crops, and 7.7 million hectares were planted worldwide (excluding China) with insect-resistant plants. US and Canadian farmers achieved a gain of US$465 million in 1996–1997, despite a 20–25% higher seed price and the imposition of a ban on reusing seed. The problem of such crops is similar to that of herbicide-tolerant plants: increasing resistance to Bt proteins will require the development of alternative resistance strategies, such as altering the protein's structure or inserting completely different toxin genes[17].

The true sustainable solution is the concept of 'integrated pest management' (IPM), which is a combination of various biocontrol means and traditional methods, such as alternating crops, growing different plant species together, creating refuges and using agrochemicals in moderate amounts. The goal of IPM is not to exterminate plant pests but to establish a system of coexistence. It has already shown promising results in Europe and in developing countries[16,18,19].

Animal breeding

Intensive animal breeding is considered to be a serious obstacle to sustainable development. Monogastric animals such as pigs and poultry compete with humans for their feed (i.e. cereals, soybeans, tapioca). Additionally, they put much stress on the environment by discharging nitrate-rich wastes[20]. Although polygastric animals such as sheep, goats and cattle exist largely on cellulose-rich vegetable material, which is difficult for humans to digest, they also compete for the land required for food production in many temperate regions. Additionally, they fuel the greenhouse effect through the production of methane estimated at 60 million tons year^{-1} worldwide[21]. It has been suggested that the application of bovine and porcine somatotropins could reduce this environmental impact by making animals more efficient but this has yet to be proved[22].

The extensive breeding of ruminants could be truly sustainable, although not efficient enough to produce enough meat to satisfy future demand. Alternative strategies for developing countries have to be developed according to regional conditions; for instance, a traditional system of combined animal rearing and plant breeding with complete waste reuse has been carried out in Southern China for over 2000 years. The increasing dissociation of feed production and intensive animal breeding, however, puts environmental stresses on both plant-production and animal-rearing regions, and also on the global ecosystem (by wasting transportation fuel)[21,23].

In the 1980s, considerable hope was put in single-celled protein (SCP), produced microbially on various organic substrates[24]. Today, SCP is an important alternative animal feed, considering that 35% of world grain is used as livestock feed, but appears to have met little success with consumers. One possible reason, in addition to lack of acceptance, is that its reliance on organic wastes as a substrate is fairly expensive. However, a more efficient method of production based on natural gas has been developed.

Genetic diversity

Finally, the preservation of genetic resources is, perhaps, the *conditio sine qua non* for attaining sustainable development. Only the availability of a large range of plant varieties and animal breeding lines will enable future biotechnologists to improve and adapt crop plants and forest trees[25], as well as livestock[26] and fish[27]. Genetic resources are currently preserved in seed banks in the form of germ plasm. Advanced plant-breeding methods are used to regenerate whole plants[28], and molecular techniques to identify the species and varieties[29].

Renewable raw materials and energy

All materials of organic origin are of major importance to sustainable development, simply because they can be grown and are renewable, as opposed to non-organic materials (metals, minerals) and fossil carbohydrates. Each year approximately 170 billion–200 billion tons of biomass is grown, of which no more than 3% is used directly by humans: 2 billion tons of wood, 1.8 billion tons of cereals, 2 billion tons of other crop plants (animal feed, organic waste and byproducts are excluded)[30].

It is forecasted that renewable materials will replace non-renewable materials on a large scale. In Brazil, some car parts are already produced from plant fibres, gums and ricin oil. Composite materials based on soybean oil are as strong as metal but much lighter and, with production costs of US$0.60–US$1.00 kg^{-1}, they are also cheaper than the plastic material vinyl ester (US$2–4 kg^{-1}).

Raw materials

The growing of plants for industrial uses (e.g. oils, fats, fibres) is certainly not a new concept. In developing countries, they are an important source of export earnings, although they compete with food crops for arable land and water. In industrialized countries, plants for non-food use are considered to be alternative outlets for the use of fallow land[31]. In Europe, 6% of maize, 1.8% of sugar, 18% of molasses, 6% of oil plants and 1.5–2% of milk proteins are used for non-food purposes[32].

Plant-derived products, such as starch, sugar, oil, fatty and other acids, enzymes, cellulose, and proteins, are already used in cosmetics, detergents, solvents and as plastic additives, lubricants, textiles, soil conditioners and other industrial products[31]. The use of such bioproducts has a considerable impact on the environment in terms of energy saving and waste reduction. One example is the use of degradable ink from soybeans for printing, which makes paper recycling cheaper.

Energy

The considerable amount of unusable, or unrequired, plant biomass from crops has caused experts to develop the concept of whole-crop biorefineries, in which products can be extracted and the remaining waste transformed into energy[31]. This technology is still not viable for a number of reasons including the facts that it is too expensive and still underdeveloped, that the raw materials are too expensive, that the markets are inadequately developed, and that an organized production chain is lacking[32].

Biofuels are considered to be an alternative to fossil fuels, although fossil fuels cannot be completely replaced by them as there is insufficient arable land to meet the total energy requirement. Examples of biofuels include:

- ethanol obtained by fermentation from plants rich in sugar and starch (e.g. beets, cereals, potatoes);
- the ethanol derivative ethyl-tertiary-butyl ether (ETBE);
- methanol from oil plants (such as rapeseed);
- organic wastes; and
- wood.

During burning, all biofuels (as opposed to fossil fuels) release into the environment only the CO_2 that they have bound recently and so do not upset the global CO_2 balance. The generation of bioethanol from organic sources, however, releases considerably more NO_2 and SO_2 into the air than do conventional production methods. Although ethanol and ETBE are best used as fuel additives in motor vehicles, methanol can be used for heating or as a replacement for diesel; its efficiency is inferior to diesel but it is rapidly biodegraded. Currently, France has 143 000 hectares set aside for biofuel production and expects to replace approximately 5% of its diesel usage by the year 2000, thus utilizing half of France's fallow land[33].

The main obstacle to broad biofuel use, however, is its high production price (US$0.70–US$1.00 l^{-1}) compared with the average oil spot price on the world market of US$0.175 l^{-1} and the US pump price of US$0.34 l^{-1} for petroleum diesel. Rapeseed-based biodiesel is slightly cheaper, at about US$0.50–US$0.60 l^{-1}, while mixtures of waste vegetable oils and ethanol would cost even less (US$0.25 l^{-1}). These estimates exclude subsidies of agricultural products but, of course, it would be preferable to subsidize biofuels in order to reduce CO_2 output. The costs would, however, still be very high compared with other options to reduce CO_2; for instance, the most efficient CO_2-abatement method in terms of carbon fixation, the conversion of sugarbeet into ethanol, is also by far the most expensive[34,35].

Therefore, in the future biofuels will probably be produced from fast-growing biomass, such as certain trees and grasses. For example, the grass *Miscanthus sinensis* yields 5–6 times more biomass per hectare than cereals or beet[30]; also, the fermentation of willow using *Escherichia coli* currently costs US$0.48 (l ethanol)$^{-1}$ (Guido Zacchi, pers. commun.) and this might be reduced to US$0.33 l^{-1} in large-scale use, which is close to the price of conventional ethanol production by yeast. The use of forest trees, however, is still too expensive and electricity production costs about three times more than from coal-powered generators, although the gap is closing. On the other hand, the wood equivalent of one ton of coal would release up to 500 kg less CO_2 into the atmosphere.

'Apart from some minor side effects, things are looking very promising!'

The main technical obstacle to biofuel production is that xylose cannot be converted by conventional microorganisms. Genetically engineered strains of the yeasts *Zymomonas* [developed at the US Department of Energy (DoE) National Renewable Energy Laboratory] and *Saccharomyces* (from the Purdue University Laboratory of Renewable Resources Engineering), which efficiently convert glucose and xylose sugars from maize into ethanol, could make bioenergy from wood cheaper. The DoE project leader J. Mielenz believes that fuel costs could be reduced to approximately US\$0.15 l^{-1}, making bioethanol competitive with oil as a transportation fuel. *Zymomonas* strains could also be used on waste products, grass and trees.

The main obstacle to biofuel progress is thus not technical but the low oil price on the world market. Falling oil prices also compromised the Brazilian gasohol programme, which is based on sugar-cane fermentation – the number of cars using ethanol fell to 30–40% of the original level.

Plant and animal wastes

The use of organic plant waste has been tackled by a number of approaches. The main products obtained are heat and alcohol, both implying problems for sustainability. Heat production becomes difficult if the generation of CO_2 has to be avoided; the cost of producing such energy could easily outstrip its value. Bioalcohol is already produced in large quantities in Europe from wine surpluses. However, the agroindustry is looking for methods to tackle difficult waste products, such as the 800 000 tons of dried citrus waste produced annually in the USA.

Animal waste has become an urgent problem for densely populated and polluted regions in Europe and the USA, primarily because of the insufficient land available to spread the manure as fertilizer. The problem can be tackled by using genetically engineered plants for animal feed; for example, the use of phytase-containing transgenic seeds as additives would help to reduce phosphorus levels in excrements[36]. A bioconverter for animal manure using thermophilic bacteria has been developed that produces biogas for heating purposes, nutrients for aquaculture and a keratinase capable of degrading hairs and feathers[37].

Waste prevention

US industry generates more than 300 million tons of hazardous waste and approximately 600 million tons of nonhazardous waste annually. To meet existing regulations, US industry spends more than US\$40 billion every year on pollution control, and waste-treatment and -disposal costs are rising faster than the growth of industrial products[38]. Experts are unanimous: instead of spending ever-increasing amounts to manage our waste mountains, it would be wiser to prevent waste.

In order to approach this goal, we have to improve the efficiency of production processes and reuse as much of the raw materials as possible, thus reducing the input of both energy and materials. This could be achieved by recycling reusable materials, replacing non-degradable substances with biodegradable compounds, applying biological extraction methods in mining, redesigning production processes to avoid waste generation and developing efficient and specific monitoring devices.

Biotechnology has, to date, made little contribution to recycling despite its great potential, except in the area of paper recycling. The treatment of aqueous and solid wastes of industrial, agricultural and domestic origin offers a number of opportunities to apply a wide range of biotechnological methods. The efficiency of these methods is based on the capacity of the organisms to degrade organic material or absorb hazardous substances. Bacteria[39], microalgae[40], fungi[41], yeasts[42] and plants[43] have already been shown to degrade organic wastes to some extent, and the fixed costs per cubic metre of bioremediation can be 10–20 times lower than incineration. Composting trials showed that certain pharmaceutical solid wastes can be broken down by 90% in 10 days of biological treatment[44]. It has also been shown that the biotransformation of waste paper to ethanol by recombinant bacteria is cost effective compared with the conventional process using yeast and added enzymes.

The principle of sustainable development requires that materials no longer used are either recycled or biologically degraded (which is, in chemical terms, the same process). Although organic materials have always been put to some use, biotechnology offers new ways to use traditional bioproducts, such as fibres, gums, waxes, leathers and silk, and different approaches to produce chemicals from biological matter. Polysaccharides, for example, are widely used as food additives (e.g. sweeteners, preserving agents), bioadhesives, absorbents and plastics.

Plastics

Microbial polyhydroxybutyrate is already produced on an industrial scale and sold as 'bioplastic' for packaging; unfortunately, this process is limited and expensive. Zeneca is producing its polyhydroxyalkanoate (PHA) product BIOPOL (approximately 1000 tons year^{-1}) at a cost of approximately US$16 kg^{-1} (Ref. 45). There are also plans to synthesize PHA in transgenic plants. Prices could be reduced by using cheap sugar; for example, Brazilian bioplastic will only cost US$1–US$3 kg^{-1}, which is four times cheaper than that sold on the international market, while BioPlastics is producing sugar-based plastics at little more than US$1 kg^{-1} (Carlos E. Roussel, pers. commun.).

The effectiveness of biodegradation, as mentioned above, depends on the environmental conditions. For example, densely packed bioplastics inside landfill sites have shown poor degradation rates. Better results have been obtained with starch granulates added to oil-derived polyethylene, which are also cheaper than pure bioplastics[33].

Cellulose, certainly the most important biomaterial, with a production of 200 million tons year^{-1}, can also be produced microbially[46], while chitin and chitosan ($>$2000 tons y^{-1}), are obtained from shells and crab and sea-urchin skeletons. They are used in cosmetics, for water cleaning, as immobilization gels, as fruit and seed preservation agents, and for packaging[47].

Mining

The prospects for applying biotechnological methods in mining are excellent, because these methods are often cheaper than conventional technologies, for example, in the detoxification of effluents. Bacteria are already used in copper and gold mining in Chile, Ghana, Uzbekistan, India and Australia. At least 25% of the copper and 33% of the gold produced worldwide comes from bioprocessing[48]. In Australia, savings of A$25 ton^{-1} in treatment costs have been achieved, while avoiding sulphur-dioxide pollution.

Efficient bioleaching, however, can only be achieved in bioreactors, where a degree of accumulation of $>$99% can be reached for metals[49]. Hence, bacteria applied to the surface of copper ore accumulated up to 11 g ton^{-1} day^{-1}, whereas leaching in reactors yielded approximately 129 kg ton^{-1} day^{-1} (Ref. 50). Genetically engineered bacteria are unlikely to improve the uptake rates because physicochemical factors at the mineral-surface–liquid interface are the limiting factors in mineral dissolution[51]. Genetic engineering is, however, likely to be used to overcome the inhibition of bacteria by toxic compounds. For instance, if the tolerance level for arsenic could be raised, bacteria would be more efficient in treating gold-bearing arsenopyrites[51].

Paper production

Redesigning production processes using biotechnological methods has been successfully undertaken in the paper and pulp industry in four different ways: (1) altering tree fibres as a result of genetic manipulation; (2) adding enzymes to reduce chlorine use; (3) purifying waste waters; and (4) removing ink from waste paper (deinking)[52].

However, the paper industry is unlikely to use enzymes in the bleaching process because they are too expensive and enzymatic treatment takes too much time[33]. The development of genetically engineered trees to help to separate lignin from cellulose may save US$100 million y^{-1}, although such wood will increase costs as raw materials represent 45–65% of the final paper price[53].

Chemical industry

The chemical industry is very interested in applying biocatalysts and genetically engineered microorganisms in order to use renewable raw materials and minimize toxic wastes without increasing energy consumption. The pharmaceutical and food industries are already applying large-scale fermentation techniques, both with and without genetic technology. Examples include thermophilic and psychrophilic enzymes working under hot and cold conditions, thus allowing optimization of energy use and a reduction of waste.

The potential of such enzymes might be even greater as a result of 'directed evolution', which has led to the production of highly efficient enzymes[54]. The use of genetic engineering in production processes leads (according to Novo Nordisk) to a 41% reduction in raw-material consumption, a 47% reduction in water consumption, a 48% reduction in steam production and a 49% reduction in electricity use.

Monitoring devices

A necessary precondition for environment-friendly processing is the development of highly specific and efficient monitoring devices. A range of biosensors and bioassays has been developed and applied to bioprocess systems. These devices can be based on catalytic elements such as enzymes, microorganisms (e.g. using bioluminescence[55]) and tissues, or on non-catalytic elements, such as receptors, nucleic acids and antibodies. However, some critics point to the disadvantages of biosensors, such as high specificity, lack of stability and short life-time[56]. Worldwide, biosensor sales were US$200 million in 1990 and predictions for the year 2000 vary from US$650 million to US$900 million[57].

Using biosensors has considerable potential in pollution prevention, even though specificity presently makes them unsuitable for mass marketing. However, it has been estimated that the US sales figures for 1998 will be approximately US$12 million, and that they will reach US$35 million by 2003, representing 12% of the environmental diagnostics market[58]. The development of living organisms, such as larvae, molluscs, lichens and plants, as pollution indicators might be better suited for commercialization. Multipurpose bioassays are also promising, for instance, in the development of multi-enzyme systems for the detection of toxic compounds in complex industrial effluents[59].

Bioremediation

Numerous laboratory trials have demonstrated the capability of microorganisms in biodegradation and biosorption but, unfortunately, these depend on many physical and chemical conditions that differ with field conditions. Genetic engineering can certainly improve a microorganism's efficiency, whereas the maximum use of their capabilities presumably can only be achieved under the controlled conditions of bioreactors. As certain industrial pollutants are not degradable by known, naturally occurring processes, it is a challenge for bioengineers to develop new bioremediation processes, as in the case of polychlorinated biphenyl (PCB) biodegradation.

Heavy metals

Plants have been shown to have the capacity to absorb heavy metals. Examples include *Thlaspi caerulescens* (cadmium and zinc), *Zea mays* and *Thlaspi rotundifolium* (lead), and *Alyssum* (nickel)[60]. The normal accumulation level of plants varies from 0.1 to 100 mg (kg plant mass)$^{-1}$ although, in exceptional cases, 1–3% can be reached, with a record of 25% by dry mass for a nickel-accumulating tree shrub[61]. Such hyperaccumulators, however, grow slowly, have a small biomass and thrive best under extreme environmental conditions (e.g. contaminated soils), thus making cultivation difficult[61]. Phytoremediation would cost approximately US$0.02–US$1.00 m^{-3} y^{-1}(including post-harvest treatment), compared with incineration costs of US$100 m^{-3}. Consequently, such plants could be used to remediate industrial or military sites.

Economic considerations

Bioremediation is considered to be far more cost efficient than traditional cleaning technologies, with possible savings of 65–85%. Waste incineration, for instance, costs US$250–US$500 ton^{-1}, whereas biological treatment costs US$40–US$70 ton^{-1} (D. Brauer, pers. commun.). It has been estimated that bioremediation of polluted soil is, at least, one third cheaper[62]; for example, the biotreatment costs are between US$50 and US$130 m^{-3}, compared with conventional costs of US$300–US$1000 m^{-3} for incineration and US$200–US$300 m^{-3} for disposal in landfills[63]. The current US market for soil decontamination has been estimated at US$1.5 billion–US$2 billion, while the US market for all biotechnology-based environmental management could even reach US$2.8 billion by the year 2000, compared with the European market (US$1 billion[64]) and the world market (US$11.5 billion), according to DEVO Enterprises. In 1996, the UK market was approximately £20 million–£40 million, of which 10–20% was for bioremediation, and it has been predicted that the bioremediation market may increase to £50 million by 2000 (Ref. 65).

Despite justified optimism for future growth, some problems are impeding further progress:

- each waste site has unique characteristics, thus requiring costly tailor-made applications;
- many industrial pollutants still cannot be degraded satisfactorily under natural conditions;
- *in situ* applications of altered microbial strains might pose significant ecological risks; and
- the technique is often time consuming.

It should be noted that adding exogenous microorganisms might not always be the best solution where indigenous populations are already *in situ* and could do well, if supplied with sufficient nutrients and oxygen[64].

Oil spills

In the specialized field of oil recovery from major oil spills, the potential, as well as the limits, of bioremediation have already been shown. The complex nature of crude oil demands the application of various microbial strains. Although over 30 genera of oil-degrading bacteria and fungi have been identified[66], it is almost impossible to produce the right microorganism balance for each type of oil[67].

The use of biofertilizers and adequate aeration has been shown to increase (by a factor of 3–5) the natural rates of oil biodegradation[68]. Also, the marine environment makes the effective application of microorganisms difficult, and genetically engineered microorganisms are presently considered unfit for this purpose; in fact, the only patented hydrocarbon-degrading pseudomonad has, so far, never been used in an emergency[68].

Conclusions and outlook

The main sector for biotechnologically supported sustainable development is almost certainly food production. Important advances have been made in developing herbicide- and pest-resistant transgenic plants but other developments of at least equal importance for the future world food supply, such as nitrogen fixation and resistance to environmental stress, are still a long way behind. The same applies to animal breeding, where qualitative improvement is still in its infancy. The application of biotechnological methods to *ex situ* conservation of genetic resources, however, is of major importance for future breeding efforts.

The production of renewable materials and energy has, for the time being, had a minor impact compared with food production, although this might change. The positive environmental impact and price advantages favour biodegradable materials from alternative crops or even byproducts. Renewable energy is, however, still not competitive, because petroleum is largely underpriced.

Major progress in the prevention of pollution has been achieved in the field of biomining and bioprocessing. The main advantages for biotechnological methods are likely to be the replacement of environmentally harmful substances with biological ones and redesigning processes to minimize energy consumption and waste output. However, this will not be possible without adequate and economically viable monitoring devices.

Bioremediation is a very promising but, unfortunately, difficult field in which no major breakthroughs can be expected soon. Microorganisms and plants have natural limits to their performance, and these limits will only be overcome by using genetic-engineering techniques.

The impact of biotechnology will not be limited to these fields. Forestry products are considered to be widely underused and should gain economic importance, and it is well known that forests play a key role in the protection of the environment. Similarly, the value of aquaculture will be enhanced by the prospect of obtaining biodegradable substances, such as chitin, from waste products. However, the biotechnological impact on transport will be limited to a rather small contribution from biofuels that, nevertheless, might be important for oil-importing developing countries.

Finally, biotechnology is expected to contribute significantly to strategies established to counteract the threat of climate change. Some experts see algal mass culture as an important means to reduce CO_2 levels in the atmosphere, complementing reforestation, in addition to using eutrophication agents such as phosphorus and ammonia to stabilize global weather cycles[69]. Equally important, of course, is the possibility of adapting crop plants to climate changes more quickly by using biotechnological methods.

It might still be too early to judge the future impact of biotechnology on sustainable development. Despite the promising results obtained so far, caution tells us that alternative approaches should also be developed. In the end, the market will decide in each case which methods will be applied to solve each problem.

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