Exploiting nature's recyclers for a cleaner environment

Expert Statement: Royal Irish Academy Life and Medical Sciences Committee

Dr John McGrath and Dr John Quinn *October 2015*

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In the late 1600s, Antonie van Leeuwenhoek (a draper, haberdasher and amateur microscopist) first described the existence of microorganisms. Today, society is acutely aware of their presence through articles describing the latest 'superbug' to challenge human health, advertisements bleaching foul looking microbes from our homes or movies depicting end-of-the-world scenarios involving flesh-eating microbial monsters.

Yet only about 5% of all microorganisms actually cause us any harm, and the reality is we could not survive without many of them. For decades microorganisms have been used to control our waste (biodegradation), purify our water (waste-water treatment), clean up our pollution (bioremediation), and keep our soils fertile and our atmosphere suitable for human habitation (biogeochemical cycling). Indeed, microbial activity is a key player in many of the major nutrient cycles—the carbon, nitrogen, sulphur, phosphorus and oxygen cycles—that facilitate life on earth: approximately 50% of the oxygen we breathe is derived from microbes.

Microorganisms display amazing metabolic ingenuity. For example, reduction of atmospheric nitrogen is the principal way of producing ammonia for agriculture. Chemically this is achieved via the Haber-Bosch process, which employs both high temperature and pressure to synthesise ammonia from hydrogen and nitrogen. Yet nitrogen-fixing microorganisms accomplish the same feat in gardens across Ireland. In fact, microbial nitrogen fixation is the only way in which nitrogen can biologically be returned from the atmosphere to the soil and thereby enter the food web. Extinction is a phrase often used to warn of impending species loss. As controversial as it seems, such extinction events rarely have an ecosystem-wide effect. In the unlikely event that those microorganisms which fix nitrogen were to die out, however, biological nitrogen fixation would cease, with major global, agricultural and economic consequences.

Microoganisms have a simple lifestyle; they feed and they divide. Sometimes this is not to our liking—food spoils, houses have dry rot, our bodies become infected. Nevertheless, this simple lifestyle also means that they play a crucial role in our lives. Microorganisms are nature's ultimate recyclers, breaking down complex molecules as sources of carbon, energy, nitrogen, phosphorus, sulphur or any other element needed for cellular growth, thereby returning carbon dioxide, water and minerals to the biosphere. Indeed, without microbial decomposition, sewage would accumulate, landfills would continually expand and fields would be infertile. Harnessing and exploiting this degradative ability in a controlled fashion has led to the practical application of microorganisms for the clean-up of environmental pollution, a process known as bioremediation.

Many examples of bioremediation exist. Anyone reading this article who owns a compost bin can be considered a bioremediation practitioner: composting is the microbial degradation of bulky organic waste. In fact, we all have our own personal compost bin—our gut—which harbours more bacteria than the total number of people who have ever lived. The microbes in our gut turn over the equivalent weight of 60 tons of food during an average human lifetime—that's equivalent to 45 small family cars.

Bioremediation can also be harnessed in more specialised situations in which human activity—especially activity since the mid-nineteenth century—has caused pollution of the environment. In this respect the principal aim of bioremediation is to degrade the pollutant of interest to such a level that it is no longer considered a hazard by regulatory agencies. Bioremediation does have its limitations, however. Most importantly its effectiveness is confined to those compounds that can be biodegraded. Additionally, in utilising a particular substrate, the microbial population may inadvertently transform the parent chemical into something that is more persistent or more toxic than the original. It is also a relatively slow process when compared to, for example, incineration. This may be problematic in particular if water courses are at risk from contamination.

For the most part, bioremediation is an effective strategy for the rehabilitation of areas affected by pollution, re-establishing the original natural environment. As such it has been applied for the restoration of soil and water, and the treatment of waste-water, industrial effluents, groundwater and gaseous emissions. Two different bioremediation strategies are routinely employed. Where *in situ* bioremediation is practiced, no material is removed from the polluted site and the introduction of nutrients and oxygen stimulates the indigenous microflora to remove contaminating chemicals. *In situ* technologies are relatively low-cost but are difficult to manage. *Ex situ* bioremediation, on the other hand, involves the excavation and removal of contaminated material for off-site treatment. Although more expensive, *ex situ* bioremediation is more amenable to process control.

Since a key requirement for bioremediation is that the contaminating chemical is capable of being biologically degraded, microorganisms must exist which are capable of metabolising the compounds of interest. These may be indigenous to the contaminated area or they may be isolated from elsewhere and brought to the contaminated site. The latter strategy is referred to as bioaugmentation. Furthermore, bioremediation is only possible where the environmental conditions are such that microbial growth can be supported. Although microorganisms have an amazing capacity to occupy almost any environmental niche—for example *Pyrolobus fumarii* grows at temperatures of up to 113°C, while *Deinococcus radiodurans* can withstand a radiation dosage that is 3,000 times greater than what would kill a human—all microbial species have defined environmental limits within which they thrive. Bioremediation therefore oftentimes involves the manipulation of environmental parameters to maximise microbial growth rate. This may take the form of an alteration to one or more of the physical properties of the site—such as pH or level of oxygen—or the addition of nutrients to stimulate growth. Like any other organism, microbes require a balanced diet, with nutrient limitation resulting in a cessation of growth. Consider, therefore, a site contaminated with oil, which is a long-chain hydrocarbon. Under such conditions the nutrient levels are unbalanced with respect to the ratio between the available carbon and soil nitrogen and phosphorus (or other inorganic nutrient) concentrations. The addition of nitrogen and phosphorus (or any other growth-limiting substrate) will therefore be required to stimulate microbial growth and remove the hydrocarbon contamination. This process of nutrient amendment is known as *biostimulation*.

On 24 March 1989, the Exxon Valdez grounded in Prince William Sound, Alaska, releasing over 40 million litres of oil into the surrounding environment. This was undoubtedly an environmental tragedy, but the Exxon Valdez disaster is also one of the most successful examples of the effectiveness of in situ bioremediation for pollutant clean-up. Biostimulation of the indigenous microbial community with a nitrogen- and phosphorus-based fertiliser over subsequent years resulted in the removal of the contaminating oil from both the Sound itself and over 100km of nearby shoreline.

The need to develop the next generation of renewable energy technologies and co-products, as well as to supply a wider range of bio-products, is clearly identified in a range of current EC policies. There is large potential to supply the marketplace with products derived from wastes, for example minerals, eco-friendly materials (such as biodegradable plastic/polymers), platform chemicals, clean water and next generation biofuels. Phosphorus is an essential part of the global food web, being required to raise crops and animals, and it is also utilised in numerous industrial technologies across the agricultural, pharmaceutical and chemical sectors. In total, around 140 million tonnes of phosphorus rock are extracted per annum, with 22 million tonnes consumed as fertiliser in Europe alone. Global phosphorus reserves are limited, and, while timelines for 'peak phosphorus' are contentious (current estimates suggest that phosphorus rock reserves may last for between 45 and 300 years), it is clear that the rock that remains is of lower grade and more difficult to access, thereby increasing processing costs. This is further exacerbated by the expected 40–50% increase in human phosphorus synthetic fertiliser usage over the next 50 years, which will be required to feed the increasing global population.

Moreover, phosphorus supplies come from just a few key countries. Indeed, Europe's phosphorus production is minimal, with Morocco, the USA, China and Russia responsible for more than 75% of the worldwide raw material production. Concomitantly, Ireland and the wider European community, which has for many years seen itself as a food-secure region, now recognises its high vulnerability to phosphorus scarcity. Security of phosphorus supply to European countries is therefore a key issue. Decreasing rock quality, Dwindling resources and security of supply are all reflected in the escalating price of phosphorous: it is now one of 20 materials listed by the EU as a 'critical raw material'. Wastewater streams offer a compelling opportunity to recover and recycle phosphorus. Some microorganisms have the ability to store phosphorus internally as a biopolymer known as polyphosphate. Bio-mining of this polymer could supply up to 30% of industrial-agricultural phosphorus demand.

As the list of chemicals used by society increases, so does our need to treat even more complex waste streams. Exploitation of microorganisms offers the potential to develop new treatment technologies for such problem wastes. Development of improved bioremediation strategies requires a multidisciplinary research effort by engineers, hydrologists and microbiologists to understand both the biochemistry and genetics of how microbial communities respond to and degrade pollutants, and to develop effective field trials and ex situ technologies for treatment of contaminated material.

It is of little surprise, therefore, that as nature's ultimate recyclers, microorganisms—whose activities have played a pivotal role in shaping our planet for the last 3 billon years—will continue to do so as we learn how best to exploit their amazing metabolic processes to control our twenty-first century waste.

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