Geomicrobiology is the study of the roles of microbes in geological processes. It seeks to understand both the geological and the ecological significance of these organisms and harness their activities in a variety of ways. As Professor Gadd, a leader in the field, made clear, fungi and bacteria play a critical role in the environmental cycling of the elements necessary for life, and their biotechnological potential is enormous – from the bioremediation of polluted land and the decommissioning of nuclear contamination to enhancing the effects of biofertilisers and urban mining of e-tech elements.

Professor Gadd's team works mostly with fungi. These ubiquitous, aerobic organisms thrive in even in the most extreme places – they are pioneer colonists of bare rock surfaces and can endure apparently toxic conditions. Their long filaments, or hyphae, allow them to explore their surroundings; they use a range of sensory mechanisms; they can signal to one another. But it is their capacity to excrete metabolites that can dissolve and form minerals, precipitate and nucleate metals that make fungi prime experimental models. That transformative ability is also the key to many remarkable applications.

Such processes enable fungi to form mutualistic symbioses as mycorrhizas with plant roots, whereby more than 80% of plant genera gain mineral nutrients and fungi receive carbohydrates in return. The hyphae also enable fungi to penetrate cracks and grain boundaries in rocks and minerals. The biomechanical force fungi can exert as they force their way into seemingly impermeable substrates is remarkable, the product of some of the highest pressures known inside living organisms.

The role of fungi in the decomposition of organic matter is well known, cycling not only carbon but, in fact, all of the stable elements that can be associated with biomass – including, inadvertently, many pollutants. They also play a role in bioweathering, the breaking down of rocks and minerals into smaller particles that is the primary source of many elements essential for life.

Professor Gadd's team has explored many facets of these processes. For instance, they have found evidence of a fungal role in the formation of clays from silicates, the largest group of minerals in the Earth's crust. This understanding has helped them to develop ways to use fungi to transform zinc silicate and zinc sulphide, as well as other ores and wastes, into other biominerals, or to release the component metals, a process called bioleaching.

There is growing interest in using such a bioprocessing approach to recycle, recover and protect the so-called e-tech elements. These strategic elements – the European Union has identified 14 of them – are needed in digital devices, but supplies are either running out or raise challenging geopolitical issues. The potential that fungi have in so-called 'urban mining' to recover e-tech
elements from waste is generating increasing interest. Professor Gadd's team has demonstrated the technique with the fungal precipitation of silver, selenium, tellurium and cobalt, for example, sometimes in nanoscale forms.

In an opposite approach, Professor Gadd's team has also produced evidence that fungi could help with the remediation of lead-contaminated land. They found that fungi can transform metallic lead into pyromorphite, the most stable lead mineral that exists. In fact, Professor Gadd noted that the detection of pyromorphite in soil around Leadhills in South Lanarkshire could be due to such biogenic action. So with the right fungi and a cheap phosphate to fuel its activity, soil contaminated by lead could be cleaned up. Another study has found that fungi could play a similar role with depleted uranium, mediating the formation of new, more stable uranium phosphate minerals.

The same bioleaching and transformation mechanisms can release phosphates from inorganic sources such as rock phosphate. These can then serve as nutrients that are easily taken up by plants. In trials in Pakistan and Vietnam, Professor Gadd's team used bacteria and fungi as biofertilisers and boost crop yields by up to 30%. In Thailand, the approach is being used to help revegetate contaminated land around a zinc smelter, as well as support the regeneration of natural forest in deforested pineapple farmland, where the soil has been washed away.

The biodeterioration of concrete is another significant area of interest. Even on relatively recent concrete buildings, the patches of lichens, fungi and other organisms indicate often extensive damage, whilst different colours can reveal mineralogical changes such as iron leaching, oxide deposition or calcite precipitation. Such effects can also be relevant to nuclear containment and decommissioning. Professor Gadd showed that a piece of barrier concrete from the Chernobyl nuclear reactor was riddled with evidence of fungal activity. Even in such an apparently adverse environment, fungi can tunnel several hundred microns below the surface in the right conditions. Professor Gadd's team has therefore worked on ways in which fungi could be used in nuclear decommissioning. A matrix containing geoactive fungi was applied to the surface of a cube of mortar loaded with cobalt. The fungi excreted organic acids that etched into the block, releasing the cobalt and taking it back into the biomass. After a couple of weeks, this biomass could be removed leaving the decontaminated mortar – minus its surface layer – behind.

Cultural heritage can be vulnerable to this ability of fungi to etch into rocks and minerals. Lichens can obliterate sculpture, for instance, stripping away surface layers completely if they come loose. Professor Gadd noted that some experts believe many such monuments could be destroyed within the next century if they are not looked after. Other materials can be even more vulnerable. In work prompted by concerns about the conservation of the Lewis chessmen, Professor Gadd's team found that fungi could attack walrus tusk (the material from which the pieces are made) and that Aspergillus niger, a common fungus that makes citric acid, can completely dissolve a sample of ancient boar tusk in just two days.

Professor Gadd has also looked at a group of sulphate-reducing bacteria that, in contrast to the fungi he has worked with, are strictly anaerobic. These organisms reduce sulphate to sulphide, growing on organic compounds or hydrogen. They are commonly found in the black muds around estuaries, where they transform toxic metals into insoluble metal sulphides that are then locked up in sediment. That ability makes these bacteria ideal for bioremediation.

These sulphate-reducing bacteria can be used along with sulphur-oxidising bacteria that produce soluble metal sulphates and sulphuric acid. This results in powerful metal leaching, a process that has become an established industry since the 1950s. For instance, about 20% of copper in the USA comes from such treatment of low-grade copper ores. A similar process can be used to clean up contaminated soil, already a multi-billion-dollar industry in the USA. A bioreactor at the Nyrstar Bodel zinc refinery in the Netherlands has been using this technology since the 1990s, to convert sulphate into sulphide and recover valuable metals such as copper, nickel and zinc.
Questions

- What work is being done to identify the deleterious effects of fungi on concrete and stone structures and hence predict when they might become unsafe?

Professor Gadd said he does not believe such research is being done in this context. He noted that when fungi and lichens are removed from buildings and cultural heritage, it can ultimately increase biodeterioration, as it spreads the organisms, increases porosity and removes potentially protective mineral patinas.

- Are there organisms that attack these benign fungi?

Professor Gadd said there are many things that feed off fungi, such as certain insect larvae, and there are mycoparasites and viruses, although he has not encountered anything that specifically attacks the fungi he works with.

- Are we missing an opportunity in Scotland to get rich through the recycling of e-tech elements?

Professor Gadd said the idea of making money from recovering precious materials from waste is not new but the need to tackle the issue is growing increasingly urgent. Bacteria and fungi could be used to help recover many such materials, for instance platinum and palladium from roadside dust, as well as the many valuable metals occurring in electronic, mine and other wastes.

- Can bioremediation be used on plastic?

Professor Gadd said some plastics are relatively simple for bacteria and fungi to attack, in contrast to metals that can only be transformed to a different soluble or insoluble form. Some plastics can be rapidly degraded in the right conditions. Fungi are particularly good at degrading long polymers.

A Vote of Thanks was offered by Professor Anna Dominiczak OBE FRSE.