Metals and Radioactive Substance Bioremediation

Mummy, how can we clean up the horrible mess where the old factory was?

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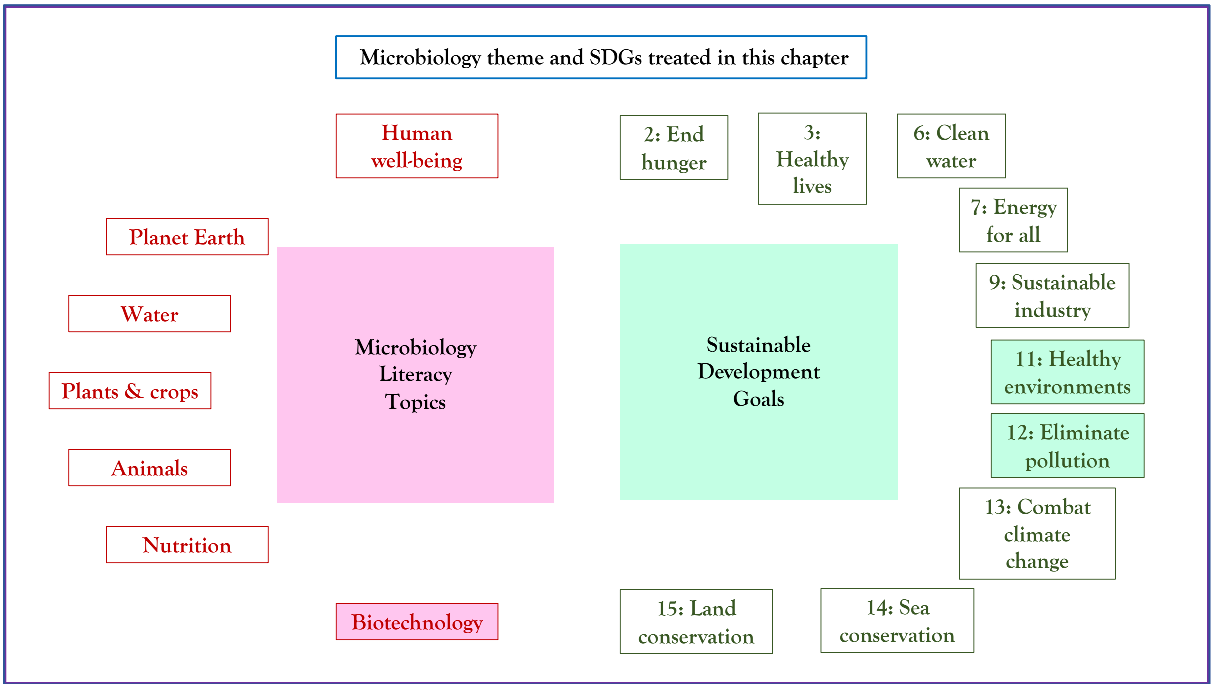
Storyline

Pollution of the environment with harmful substances is a major problem that affects almost every country in the world. We all contribute to pollution by consuming the Earth's resources and disposing of our wastes. Likewise, almost all industrial activity can cause pollution unless care is taken to protect the environment. Such activities include mining, oil and gas, transport, energy, farming, technology, manufacturing, food, construction, healthcare and electronics industries. Radioactive wastes are produced by the nuclear energy and nuclear medicine industries and the manufacture of nuclear weapons. It is important that we clean up pollution to protect the health of people and wildlife, and the environment. This Topic Framework describes how we can use biology to clean up (remediate) pollution by metals and radioactive substances in soils and waters (bioremediation), and how this can contribute towards the Sustainable Development Goals for Healthy Environments and Eliminating Pollution.

The Microbiology and Societal Context

The microbiology: the importance of clean soils and waters; pollution of the environment with toxic metals and radioactive substances; what happens to pollution in soils and groundwater; using biology to clean up pollution. *Sustainability issues*: healthy environments, eliminate pollution.



Metals and Radioactive Substance Bioremediation: the Microbiology

1. ***The importance of clean soils and waters.*** *"There can be no life without soil and no soil without life"* (Charles E. Kellogg, 1938). Soils support life on Earth. Without soils there would be no plants, no agricultural crops, and few habitats for terrestrial life. Soils contain nutrients that help plants to grow. Soils are a habitat (home) for living organisms, including microorganisms. Rain water soaks through soils into the ground and forms a resource called groundwater. Billions of people across the planet rely on groundwater wells for their drinking water supply. Soils can even help to prevent flooding by soaking up excess water. They also absorb carbon dioxide from the atmosphere and slow the rate of climate change. Microorganisms are an essential part of soil, they help to recycle soil nutrients, they break down dead organic matter, they fix nitrogen from the atmosphere to help plants grow.

2. ***Human activities have polluted the environment with toxic metals and radioactive substances.*** Many human activities and industries have introduced harmful substances into the environment at levels that can be dangerous, causing pollution. Metals and radioactive substances are examples of harmful substances. They are often toxic, which means that they cause illnesses, and can even kill living things including humans.

Sources of metal pollution can be mining, smelting (extracting metals from rocks), burning of fossil fuels, car exhaust fumes, application of fertiliser and pesticides and waste disposal. The metals that we are most concerned about include arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc. The nuclear industry is the largest source of radioactive substance pollution, and includes uranium mining, manufacturing nuclear fuel from uranium minerals, nuclear energy production, nuclear fuel reprocessing (recycling), and nuclear waste disposal.

Pollution of the environment not only harms humans, it also harms wildlife and the tiny microorganisms that live in soils and waters. Pollution can cause soils to become degraded and incapable of functioning as normal. Because of this, it is important that we clean up pollution and make sure that land is safe for us to use, especially after it has been used by industries.

3. ***General principles for remediating pollution by metals and radioactive substances.*** It is very difficult to clean up pollution, especially pollution from metals and radioactive substances, because they cannot be destroyed. In this instance there are only two options: A) remove them from the environment and dispose of them safely e.g. in a special landfill, or B) make sure that they are in a form that cannot reach or cause harm to most living organisms. The first option is very expensive because it costs a lot of money to dispose of toxic waste in special landfills. There are a number of ways by which you can achieve Option B, such as using chemicals, constructing physical barriers, or by using biology, including microorganisms. This topic describes how we can use biological processes to remediate (clean up) polluted soils and waters, a process which we call bioremediation.

Let's explain Option B in a bit more detail. In order for pollution to cause harm, it needs to be mobile in the environment. Think of the rhetorical question "*if a tree falls in the forest and no one is there, does it still make a sound?*" Of course the tree still makes the air vibrate with sound waves, but if there are no ears to receive those waves, then you can argue that there is no sound. Moving back onto our topic of pollution in the environment, if there is nothing near the pollution and it cannot be transported towards anything (i.e. there is no-one in the forest) then it cannot cause harm (i.e. the sound is present but no-one will hear it). This is really important to understanding whether metals and radioactive substances can cause harm or not. We will use two simplified examples to illustrate this point. Imagine a toxic metal was spilled onto the ground at an old industrial site in the middle of nowhere:

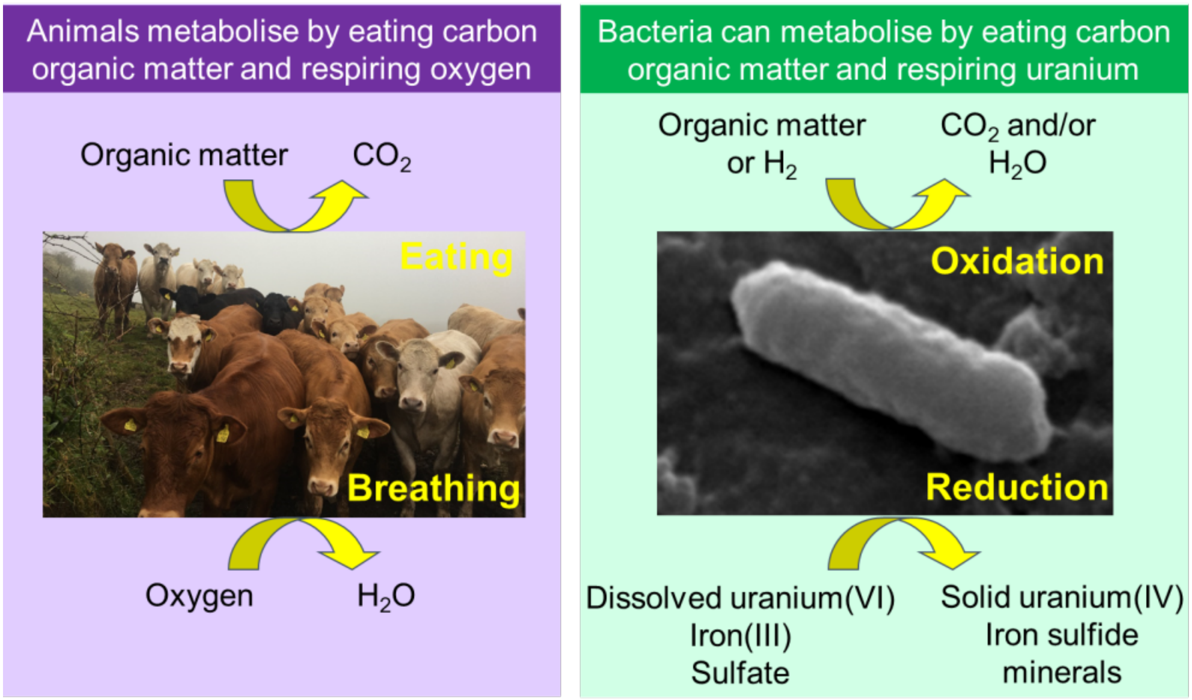
1. If the pollutant dissolves in water, it could travel through soils and reach groundwater which is used to supply drinking water for people, or it could reach rivers or lakes which contain wildlife. However, if we can change the pollutant into a form that doesn't dissolve in water (i.e. make it insoluble), it will prevent the pollutant from reaching a place that it could cause harm
2. If the pollutant forms dusts, these could be blown long distances by the wind and then inhaled (breathed in) by people and wildlife. However, if we can prevent dusts from forming, then there would be no way for the pollutant to reach anywhere where it could cause harm.

Of course, things in the real world are a lot more complicated than this, but the principle of preventing pollution from causing harm is exactly what we try to do.

4. ***Using biology to remediate pollution by metals and radioactive substances***. As mentioned above, metals and radioactive substances cannot be destroyed, so to remediate this type of pollution we need to make sure that they are in a form that cannot reach or cause harm to most living organisms. So how can biology do this? Let's work with our examples 1 and 2 again, but with real world problems.

- **Radioactive substances in groundwater**. Some nuclear sites have caused groundwater to become polluted with radioactive substances. For example, uranium is present in groundwater underlying the Old Rifle former uranium works at the US Department of Energy Rifle site in Colorado (see photo below). In the past, the waste from the uranium works was stored on site. Rain water washed through the waste, dissolving the uranium and transporting it into the groundwater. Now all the waste piles have been removed, but uranium dissolved in groundwater still remains below the surface. To treat this pollution, scientists have been investigating how we can use microorganisms to transform the uranium into forms that cannot reach most living organisms. Certain bacteria can remove uranium from groundwater by using their metabolism. They cause the dissolved uranium to become insoluble and precipitate from groundwater as solid uranium minerals. This prevents the uranium from causing harm because it is trapped underground where it cannot reach most living organisms.

So how do they do it? Let's start with a more familiar type of metabolism. All animals and people metabolise (make energy to grow and reproduce) by respiring (breathing) oxygen from air and eating carbon from food. Bacteria can metabolise in many different ways – some don't need oxygen and some don't even need to eat carbon. Living below the Old Rifle site are bacteria that actually respire uranium, iron and sulfur! So instead of respiring oxygen and producing water vapour like we do, these bacteria respire dissolved uranium and produce solid uranium minerals. This process is illustrated in the diagram below. Bacteria are doing this process all the time, especially where there is very little oxygen, like in the ground. But sometimes they aren't doing it fast enough, so to speed things up we can feed them more carbon organic matter. The photo above shows scientists preparing food for these bacteria. This is pumped into the ground and causes the uranium-respiring bacteria to produce more insoluble uranium minerals and so remediate the polluted groundwater. Not only this, the other bacteria make iron-sulfur minerals that also help to trap the uranium underground.



Using microbes is often cheaper than other remediation technologies. For radioactive substances, being able to treat this pollution in the ground has added benefits because it means that the groundwater doesn't need to be pumped to the surface for treatment, where it would be able to harm people. However, microbial processes can be slower than physical or chemical processes.

- **Metal mining**: At mine sites, rocks are removed from the ground, crushed into powders, then processed to remove the metal of interest, and the waste is disposed of by piling it up in heaps (spoil heaps). Usually only one metal is extracted from the rock, and the leftover waste material often contains other metals which are toxic. Not only this, powdered rock easily forms dusts, and therefore there is a high risk that the waste will be blown away by wind and cause harm and pollution elsewhere. However, if we can grow plants on the spoil heap, this will prevent dusts from forming. Have a look at the photo to the right. This area was previously a lead mine. Lead is a highly toxic metal that used to be used in water pipes and was also added to petrol/gasoline. The bumpy material in the foreground is the spoil heaps, but it has been covered with a thick layer of plants and soil. Even the strongest wind is unlikely to make dusts here! The soil formation and plant growth happened naturally at this particular mine, but this isn't always the case e.g. see the image at the beginning of this Topic Framework. At other mine sites, bioremediation can be performed by seeding spoil heaps with special metal-resistant plants

and their associated microbial communities (bacteria, archaea, fungi) to speed up the process. In fact sometimes special plants are used. These can not only cope with metal pollution, they are really good at extracting metals from the ground so help to clean up the pollution (a process called phytoextraction i.e. extraction by plants). Remember that these plants would not be growing without the support of microorganisms present in the soil to recycle nutrients, fix nitrogen and breakdown organic matter.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages** (*improve health, reduce preventable disease and premature deaths*). Remediating pollution decreases the chance that people will be exposed to toxic substances and their harmful effects on health. When old industrial sites are cleaned up the land can safely be reused for new buildings or parks, or wildlife can thrive there. Bioremediation can be a sustainable and environmentally-friendly way to clean up pollution. It is especially useful because it can be done without needing to dig up the polluted soils and water, and this means that the chances of health problems being caused during the remediation process are very low.
- **Goal 6. Ensure availability and sustainable management of water and sanitation for all** (*assure safe drinking water, improve water quality, reduce pollution, protect water-related ecosystems, improve water and sanitation management*). Cleaning up pollution at old industrial sites decreases the chance toxic substances will enter groundwater, streams and rivers. It also means that drinking water supplies and aquatic ecosystems are protected. Bioremediation can be a sustainable and environmentally-friendly way to clean up pollution.

Potential Implications for Decisions

1. Community policies

a) Local environmental consequences (pollution of public spaces and local water bodies)
b) Health costs associated with pollution

2. National policies

a) Environmental pollution
b) Ensuring safe drinking water supplies
c) Making sure the polluter pays the costs of clean up
d) Choosing the best method for remediating pollution

Pupil participation

1. Class discussion of the issues
a) associated with pollution and its clean up
b) around nuclear energy, which is a low carbon source of energy so potentially better for limiting climate change but causes issues with dealing with radioactive substances in waste

2. Pupil stakeholder awareness
a) Can you think of any other ways that pollution can be cleaned up?
b) Why do you think microbes are a good way to clean up pollution?

c) Why do you think that most metal mines only extract one metal of interest? Could there be a better way of doing things to make less waste? How could we make this happen?

3. Exercises

a) What are the consequences of doing nothing in response to pollution?
b) How can you make sure that the remediation work is paid for? If the firm has gone bust who should pay for the work?
c) How can we tell if a soil is clean enough? What is an acceptable level of pollution e.g. none, some, how much?

The Evidence Base, Further Reading and Teaching Aids

1. The Devil We Know (2018) – a Netflix film about environmental pollution
2. Erin Brockovich (2000) – a film about chromium groundwater pollution
3. More information on the Old Rifle site described in this topic framework https://www.lm.doe.gov/Rifle/Fact_Sheet-rifle.pdf
4. More information on the former metal mining site described in this topic framework https://www.bgs.ac.uk/mendips/localities/priddy.html
5. Teaching resources for using bioremediation to clean up other forms of pollution e.g. oil spills https://www.teachengineering.org/lessons/view/cub_lifescience_lesson04

Glossary

Archaea – single celled microbes with a simple cell structure. They look very similar to bacteria but their genes are very different.

Bacteria – single celled microbes with a simple cell structure.

Bioremediation – using biology to clean up (remediate) pollution.

Carbon dioxide – a gas with one carbon atom and two oxygen atoms.

Climate change – rapidly increasing global temperatures caused by human activity, mainly by releasing carbon dioxide to the atmosphere by combustion (burning).

Dissolves/dissolved/dissolving – the process when solid substances become incorporated into liquids, forming solutions. Substances that tend to dissolve are called soluble, substances that do not tend to dissolve are called insoluble. The opposite of dissolving is precipitating.

Fungi – single celled or multi-celled organisms, including microorganisms (like yeast) and macroorganisms (like mushrooms).

Groundwater – fresh water that is found in the ground e.g. in the pores (between particles) or fractures (cracks) of soils, sediments and rocks.

Habitat – home, the conditions where particular organisms like to live.

Inhaled – breathed in.

Insoluble – substances that remain in the solid phase and don't tend to be found in liquids.

Landfill – a place where wastes are disposed of in the ground.

Metabolism/metabolise – making energy to grow and reproduce, involves the movement of electrons in redox reactions. Also see respiration.

Metals – chemical elements that readily form positive ions and metallic bonds. Most metals are solid at room temperature and have a known crystal structure. They are shiny, can be soft (like gold) or hard (like tungsten). Some metals are very soluble (like sodium), and some are very insoluble (like tin). Many metals are essential nutrients, we need them in our diet to be healthy. Other metals are toxic and cause harm.

Microbes/Microorganisms/Microbial – organisms that are so small you need a microscope to see them. Include bacteria, archaea, fungi, viruses, protozoa and algae.

Microbial communities – collections of microorganisms that are living together and interact with each other. They can include many different types (species) of bacteria, many different types of fungi and so on. There are many ways that microbes interact. Some microbes may act as predators and eat others. Some microbes may be decomposers and eat waste materials produced by others. Some microbes will help cycle nutrients and make them available for others.

Mine/mining – excavating rocks and minerals from the ground that contain valuable/useful materials, like metals or coal.

Minerals – a naturally occurring solid material, with an ordered crystal structure and a defined chemical composition. All rocks are made of minerals. Minerals are formed by geological processes and they are inorganic, which means they are not made by living organisms. Common examples of minerals are quartz (SiO_2), rock salt (halite, NaCl) and fool's gold (pyrite, FeS_2).

Nuclear – related to the nucleus of an atom. In this article it refers to the energy produced when the nucleus of an atom breaks apart (fission), or when two nuclei join together (fusion). The nuclear energy industry uses this process to generate electricity. First uranium minerals are mined and processed to make nuclear fuel. This undergoes nuclear fission in special nuclear reactors, and the energy drives turbines to make electricity. Another use of nuclear energy is in nuclear weapons (atomic bombs). The waste products from making electricity and weapons are called nuclear waste and are highly radioactive.

Nuclear fuel reprocessing – once nuclear fuel has been used to make electricity it can be recycled in a process called 'nuclear fuel reprocessing'.

Nutrients – substances that are essential for living organisms to be able to survive, grow and reproduce. These include vitamins and chemical elements which are sometimes referred to as mineral nutrients. Animals also need proteins, carbohydrates and fats, and get their nutrients from the food they eat. Microbes and plants can get nutrients directly from the environment, for example from soil.

Organic matter – carbon-based compounds that are mostly (but not always) produced by living organisms. These include the waste products of metabolism and the breakdown products that form during decay and decomposition.

Oxidise/oxidation/redox – a chemical process where electrons are lost (donated). When a chemical is <u>ox</u>idised, at the same time another chemical must be <u>red</u>uced. These types of reactions are called <u>redox</u> reactions and are used in metabolism to make energy.

Pollution/polluted/pollutant – substances that are released into the environment by humans at levels which can cause harm to living organisms.

Precipitate – the process when liquid substances tend to crystallise and form solids. The opposite of precipitating is dissolving.

Radioactive – elements or certain forms of elements (isotopes) that are unstable. For example all types of uranium are radioactive, most carbon is not radioactive (carbon-12, carbon-13) although carbon-14 is radioactive (this is the form used in radiometric/carbon dating). To become more stable, radioactive elements decay. This means they emit energy in the form of particles or waves. If this energy is absorbed by living organisms it can cause harm, which is why all radioactive substances are classed as toxic. Some radioactive elements are much more harmful (like polonium) than others (like carbon-14).

Reduce/reduction/redox – a chemical process where electrons are gained (accepted). When a chemical is <u>red</u>uced, at the same time another chemical must be <u>ox</u>idised. These types of reactions are called <u>redox</u> reactions and are used in metabolism to make energy.

Remediate/remediation – clean up, make better, improve.

Respire/respiration – a type of metabolism where chemical energy is made by redox reactions. For example animals and humans breathe oxygen and eat organic carbon, and in our bodies these undergo chemical reactions to release energy. In fact the oxygen is reduced and the glucose is oxidised.

Smelting – extracting metals from rocks by heating.

Soil – the material at the surface of the Earth where plants grow. Soils contain minerals, organic matter, water, gas and living organisms, including microorgansims.

Spoil/spoil heaps – leftover waste materials after mining, including rocks and minerals.

Sustainable Development Goals – 17 targets set by the United Nations "to achieve a better and more sustainable future for all".

Terrestrial – lives on land, opposite to aquatic.

Toxic – causes harm to living organisms for example illness or even death, poisonous.

Uranium – a naturally-occurring radioactive metal, used to make nuclear fuel and nuclear energy.