Recycling and Biorecovery of Waste Materials

Dad: I want to become a bio-engineer and contribute to the survival of the planet. Where do I start?

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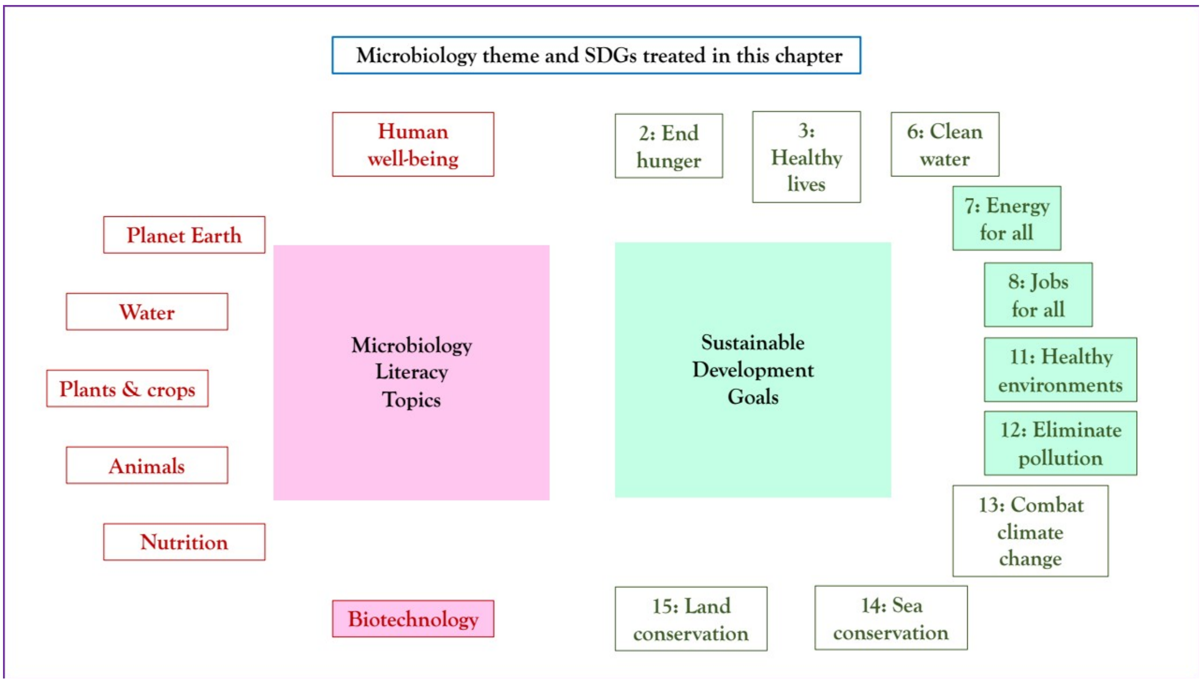
Storyline

Micro-organisms, just like people, try to make a living by using substances around them as food and converting them into cell materials. This way they survive and possibly even grow and thus create the next generation. By trial and error, they find new ways to use different substrates to build up new cell material or sources of energy. This process, in combination with the survival of the fittest, ensures that micro-organisms gradually evolve and become more specialized at certain tasks. In our industrial society, we produce side-products and waste streams that need treatment to be rendered safe. By carefully considering what happens in nature, we may enrich and recover some organisms, or teams of organisms, which are helpful for degrading our 'wastes' and, in some cases, for even recovering some of the raw materials used in production processes. Yet, let us not misunderstand this happy state of affairs: the micro-organisms are not doing the job to please us human beings; they are just exploiting a situation for their own benefit, to grow. The important feature of a bio-engineer is that he/she tries to make a balance in which both parties – we and the micro-organisms – benefit from the overall waste processing and bio-recovery process. In other TFs, the involvement of micro-organisms in water treatment and energy (biogas) production are discussed. In this TF, we focus on some different aspects of bio-engineering in which micro-organisms can be used to benefit the sustainability of the planet.

The Microbiology and Societal Context

The microbiology: microbial biodegradation of wastes; biostimulation; bioaugmentation; resource recovery; electromicrobiology; bioengineering. *Sustainability issues:* bioenergy; economy and employment; environmental pollution.



Recycling and Biorecovery of Waste Materials: the Microbiology

1. ***Cleaning of waste gases***. When organic matter is buried in soil or thrown into water, micro-organisms will make use of this matter to grow. By doing so, they consume all the oxygen in the region of the decaying organic matter. When all the oxygen is gone, another group of micro-organisms – the anaerobes, which grow without oxygen – takes over and produces gases such as methane (CH_4; greenhouse gas and flammable), hydrogen (H_2; flammable), hydrogen sulfide (H_2S; toxic, stinks like rotten eggs; also called sour gas), ammonia (NH_4; toxic, stinks) and volatile organic compounds (VOCs; stinky gases; sometimes toxic). These gases can move to the surface of the soil or water. Here they come into contact with other micro-organisms that can again transform these compounds and still extract a bit of energy out of them by combining them with oxygen.

RedOx reactions during decay of organic matter.
Organic matter is full of electrons carrying energy. Microbes can extract electrons from the organic matter in what we call an **oxidation reaction** (organic matter is the *electron donor*). When the microbes have used the energy, they need to put the electrons somewhere. This is usually done by placing them on oxygen (oxygen is the *electron acceptor* in this case). This is called a **reduction reaction.**
This process can be compared to when you get energy out of eating your favorite sandwich and breathing in air. You oxidize the organic carbon in the sandwich with the oxygen from the air, and get energy out of it. The carbon becomes CO_2 and the oxygen is transformed to water vapor.

We can use the micro-organisms that we find at the interface of the soil and water surface to clean up waste gases produced by human activity. By providing a good environment for these micro-organisms (peat, bark or other surfaces for them to grow on) several technologies such as trickling beds, scrubbing towers have been developing where waste gases enter from the bottom and water is sprayed from the top over the micro-organisms. Fig 1. gives a view of such a system. Such designs are based on a clever combination of physics, chemistry and microbiology.

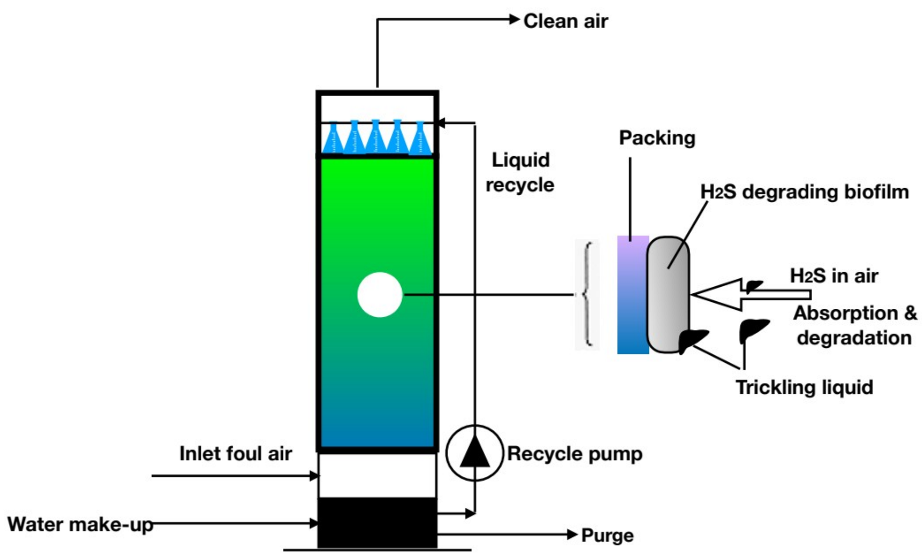


Fig 1: Summary scheme of a bio-filter in which micro-organisms grow on a carrier and convert the gaseous compound, H_2S, to sulfur powder.

In animal husbandry, for example, the emission of foul odors (particularly ammonia) can be curbed by installing large sized bio-beds and bio-scrubbers. The latter harbor nitrifying bacteria, which convert the volatile ammonia to water-soluble nitrate. The liquid that comes out of the bottom can then be used again as mineral fertilizer to grow crops.

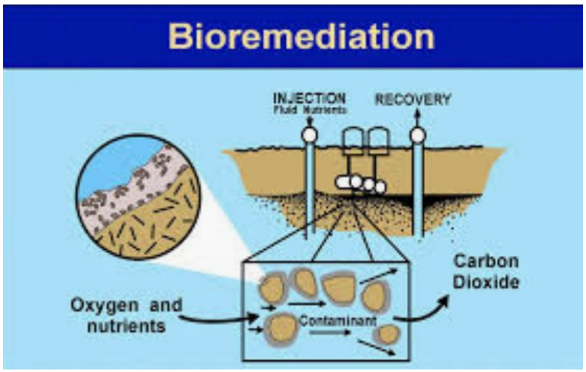
In the large-scale **petrochemical industry**, hydrogen sulfide can be washed out of process gases. By means of a very clever reactor design, the sulfide oxidizing bacterium *Thiobacillus* is kept under limited oxygen supply and the sulfide is converted into sulfur powder. This sulfur powder can be re-used as bio-pesticide.

Also gases having toxic levels of volatile organic compounds can be turned to healthy air by passing them over a biofilter in which bacteria degrading such organics (e.g. chlorinated molecules), are maintained by giving them a limited amount of biodegradable compounds. Commonly, a natural substrate as tree bark or wood chips serves as matrix through which the gases easily can pass and on which the bio-cleaning micro-organisms reside.

2. ***Soil bioremediation.*** Numerous top soils, and particularly the underlaying deeper layers, have been polluted by the discharge of oils (hydrocarbons) and chemicals. Pollutants which remain in the top layers can be removed by excavation of the soil which then receives special treatment, such as burning followed by waste gas cleaning. For the deeper soils (down 10 to 50 m below the surface), excavation is too expensive and invasive, so alternative methods have been developed.

Over the past decades, a variety of elegant processes have been developed in which these deeper soils can be cleaned with the help of micro-organisms. These **bioremediation** processes are mostly based on adding sufficient nutrients (such as nitrogen and phosphorous) and improving growth conditions (optimizing pH, providing water, electron acceptors such as nitrate or sulfate, and a food source such as lactate) to the soil, a process called **biostimulation**. When the conditions are favorable for the micro-organisms naturally present in the soil, they can degrade, grow and, in the process, degrade the pollutants around them, thereby restoring the soil system to a clean and healthy condition.

In some cases, the conditions in the subsoil can be perfect for bioremediation, but micro-organisms with the necessary capabilities are not present. This can be rectified by obtaining a micro-organism or a team of micro-organisms from another location, amplifying the population, and injecting these into the target subsurface. This process is called **bioaugmentation**. The soil and subsoil system is static (= not mixed). This means that a bio-engineer needs to carefully design injection and pumping systems so that the added organisms and the components they might need are spread all over the large volumes of soil and aquifer that need to be treated. The industry of soil clean-up by bioremediation and bioaugmentation is worldwide quite extensive and ingenious. Although such bioremediation practices often require long times to complete (sometimes even decades), they are effective and allow the soil and aquifer systems to return to their pristine conditions.



3. ***Composting (and what about plastics)?*** In many countries, sorting at home is a common practice. One collects the biodegradable parts (kitchen and food waste) in the green bin. In cities, the latter goes to a composting facility. The industrial process is based on gently blowing air into the organic matter. The micro-organisms present in the collected materials thus have an environment with plenty of food and also oxygen to respire and oxidize organic molecules. They start to grow, multiply and convert the organic matter into microbial biomass and CO_2. When we humans are exercising with plenty of people in a small room, the body heat gives rise to a temperature increase in the room. When millions of micro-organisms are intensively eating and metabolizing the organics (´exercising´), they produce so much heat in the composting facility that the temperature goes up to 50°C or even 75°C. Because the micro-organisms cannot perform well at these high temperatures, a combination of aeration and concomitant cooling of the biomass is normally practiced. Gradually, over a period of weeks, the initial mix of waste organics is converted to microbial cells and carbon dioxide. In a final phase, the microbes run out of food and die. The high temperatures and the lack of food also ensure that any harmful micro-organisms also die, thus providing a good sanitation process. The remains of all the microbes are rich in minerals and large, stable organic polymers which sorb and hold water. The latter are often called humus, and humus plus remaining plant residues and minerals is called compost. This material is of major value to plant growers because it is a matrix which slowly releases its components (water, minerals, organics) to the surrounding soil in general and to the growing plant in particular.

And why are plastics not compostable? Microbes are very good at constructing complex molecules, using enzymes, but also at deconstructing them into their component units, reversing the synthetic process, sometimes using the same, sometimes different enzymes. Natural polymers such proteins, cellulose, lignin, etc. are constructed in such a way that micro-organisms can always find a way to cut them into smaller pieces, which can then be channeled into metabolic routes. Synthetic plastics made by chemists, however, are very long, dense polymers and physically structured in a way that the enzymes do not find points where they can start to break the chains. Even starting at the end of a chain is often difficult.

> Natural polymer breakdown by micro-organisms can be compared to climbing a tree; lots of side branches and rough patterns where you can hold on to. Plastic polymer breakdown is more like climbing up a firemen's post; very smooth and no place to hold on.

In fact, many of the chemicals and materials we use today, have been designed long ago when the philosophy was to create long lasting (stable) products. It is only relatively recently that our philosophy has changed to create easily-degraded products to facilitate their recycling and avoid their accumulation as waste in the environment. Currently, in view of the massive amounts of plastic wastes along our roads, in our landfills and water bodies, there is a major effort to learn to design polymer molecules which could combine the good functional properties of plastics, on the one hand, and be biodegradable at the end of use, on the other.

But what to do with all the existing (and growing) plastic in the environment? Currently, there is a major effort to discover or grow micro-organisms which have evolved the trait to be able to produce specific enzymes which can degrade the most commonly found waste plastic. This, however, is proving to be difficult, though progress is being made. The challenges are enormous, both on the part of the plastic producing and the environmental biotechnology industries. It is essential that current and future generations find biological ways to break down plastics, certainly in industrial facilities such as the biofilters in section 1, but also in the natural environment, through bioremediation/bioaugmentation approaches discussed in section 2.

4. ***Micro-organisms can produce and use electricity.*** In section 1 it was already discussed that all living beings live by moving electrons (RedOx reactions). Humans, animals and most organisms all use oxygen as an electron acceptor. Now it turns out that a certain group of micro-organisms can also live without oxygen. These are the so-called anaerobic micro-organisms. This group can use water soluble components such as nitrate or sulfate as their electron acceptor. Within the group of anaerobic micro-organisms there are also certain microbes that can use solid metals as an electron acceptor. Conversely, some micro-organisms seem also be able to grow with CO_2 and electrons coming from metals or conductive surfaces. These are very unique properties!

Bio-engineers have made use of these microbes for the conversion of waste organic matter into a small amount of electricity. This can be done by installing a conductive material called an electrode (for example a piece of charcoal) into an anaerobic environment, for example, the sediment on the bottom of a pond. The microbes can oxidize the organic matter present and deliver the electrons on the electrode (the anode). When the electrode is connected via a wire to another electrode (cathode) at the surface of the pond where oxygen is present, the electrons can flow from the organic matter via the microbes onto the electrode (anode) via a wire through an electricity-using device (for instance, a lamp or an engine) to the other electrode (cathode) and finally onto oxygen. In this way, micro-organisms can power a small lamp. The concept of microbially-produced electricity is currently explored to power sensors and clean up specific types of pollutants in wastewaters and sediment systems.

Relevance for Sustainable Development Goals and Grand Challenges

In order to maintain a healthy planet, processes as described above are highly needed and should be further developed. The challenges are twofold: 1) biotechnological processes must become more precise. The engineer should be able to manage the micro-organisms so that they perform more rapidly and more directed towards a particular target, for instance a well-known pollutant. The way to achieve this can be by selecting certain micro-organisms from nature, or by intelligently combining species into teams which are highly complementary and performant. It can also be based on the bioengineering of microbial species which have traits thus not found in nature. 2) Society will need to develop more confidence in micro-organisms, also in bioengineered species and teams of such species, for instance to degrade a plastic polymer that is not being used anymore. The general public has learned to accept the duality of a great variety of technologies (think of the combustion engine) and it should also appreciate that bioengineering can provide safe and performing bio-processes, notwithstanding the fact that micro-organisms just as all biology, constantly evolve and thus have a certain level of unpredictability.

In the above sections, various examples are given where micro-organisms are very helpful in removing waste materials. This is only the first step to consider. The next step is that while converting the waste materials, useful products can be created: think of organic and mineral fertilizers, compost, small molecules (chemical building blocks or bio-pesticides), energy, etc. It is also important to note that, on average, a recovered material, even of the same quality of new raw materials, will only be valued at a fraction of that of the original; the public needs to be educated so that reclaimed materials are accorded equal economic values to new the raw materials. Overall, the domain of implementing bio-catalysis with engineered and controlled conditions offers a vast amount of challenging opportunities and possibilities for dealing with environmental sustainability in the coming decades.

- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all** (e*nsure access to clean, renewable and sustainable energy, and increase energy use efficiency)*. Recycling can liberate energy from waste that can be used as an alternative to fossil fuels
- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all** (p*romote economic growth, productivity and innovation, enterprise and employment creation)*. A full commitment to a circular economy and zero waste will create significant employment
- **Goal 12. Ensure sustainable consumption and production patterns** *(achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices)*. A reduction in waste production, and the recycling of existing waste, are essential to sustainability.

Potential Implications for Decisions

1. **Individual**
    a. Cooperate with separation at source of wastes
    b. Support biotechnological approaches to clean-up, recycle and upgrade
    c. Don't be afraid of micro-organisms
    d. Stimulate microbial growth in your garden

2. **Community policies**

a. Invest in various biotechnologies which allow to clean and recover resources, for example community composting.
b. Take care of the local microbial health by not using pesticides and by initiating proper waste treatment schemes

3. **National policies**
   a. Provide rules and regulations which are supportive towards bio-recycling
   b. Support the upgrading to full economy value and consider products by their specifications, not by origin.
   c. Instill awareness on the use of biotechnology/bio-engineering for the public good

Pupil participation

1. ***Class discussion of the issues associated with the clean bio-technology*** and the common 'yuck' factor related to recovered materials

2. ***Pupil stakeholder awareness***
   Most microbes are positive and bring about processes and conversions which are needed for our well-being. Can you list a set these positive processes?

3. ***Exercises***
   - Search in the supermarket for plastics that claim to be biodegradable. How would you test if this were the case?
   - Search in your region a site where the soil in the past was very much polluted (often called brownfield) and which has been cleaned and redeveloped for housing of other purposes.

The Evidence Base, Further Reading and Teaching Aids

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Glossary

Bioaugmentation: a method in which special micro-organisms are introduced to achieve a certain process.
Biobeds/Biofilters/Bioscrubbers: technical systems in which micro-organisms are used to clean air and gases and even recover certain valuable products.
Bio-electrochemistry: a field of study that focusses on the electron transfer and concomitant electrical currents generated or used by biological systems.
Bioremediation of soils: technologies by which soil conditions are created so that the natural organisms degrade pollutants and restore the soil in its capacity to deliver healthy groundwater.
Biotechnology: combination and exploitation of technology and biological systems for specific purposes, for instance, cleaning of polluted streams with microorganisms.
Composting: by gently supplying oxygen and removing excess heat, the organics are converted to a valuable plant growing matrix.
Petrochemical industry: industry that produces organic products such as petroleum, plastic, rubber and fiber raw materials from oil and gas.