Bacterial odours: a way of communication

Mum, why does the fridge smell so bad?

Picture by Viviane Perraudin

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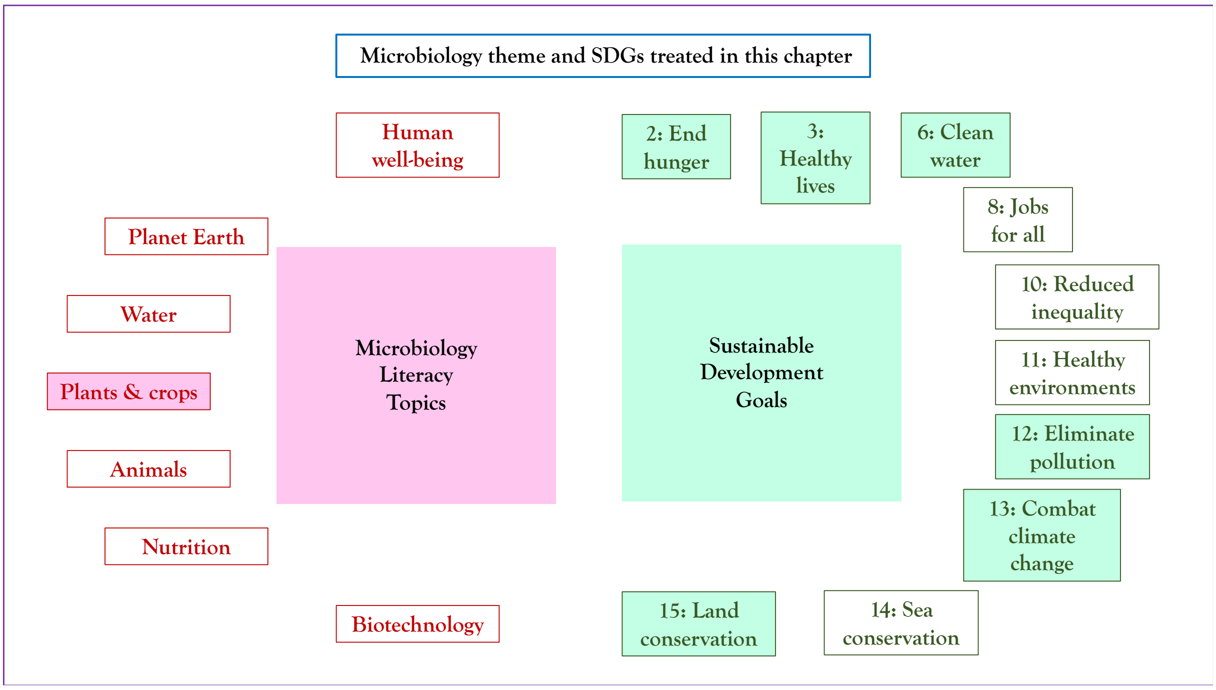
Storyline

Communication, i.e. the exchange of information, is the basis of interactions between living organisms. The universal language used by all organisms to communicate is not speech, but the exchange of chemical signals. Some of these signals have the particularity of being transmitted through the air from one organism to another: they are so-called "volatile" compounds, commonly known as "odours". Bacteria engage in mutualistic relationships with plants and volatile compounds play an important role in maintaining this good relationship. When plants smell bacterial odours, they produce more roots, grow better and are better able to withstand many environmental stresses, such as drought or heat. Bacterial odours also act as warning signals to plants, helping them to defend themselves against natural enemies, such as fungi that cause disease and significant crop losses. Protecting our health and ensuring sustainable food production requires environmentally friendly agriculture. The use of bacteria and their volatile compounds is a promising alternative to the use of synthetic fertilisers and pesticides, as these bacterial volatiles are naturally degradable and will not accumulate in the soil or be washed away by rainwater into our water tables, rivers and lakes.

The Microbiology and Societal Context

The microbiology: bacterial metabolism; fermentations; secondary metabolites; volatile compounds; chemical ecology; plant-microbe interactions; plant growth promoting rhizobacteria; synthesis of phytohormones by bacteria; biological control; biopesticides; recycling of organic matter. *Sustainability issues:* sustainable food production; sustainable crop protection; water and soil protection; protection of human and animal health; microbial biodiversity; reduction of greenhouse gases.



Bacterial odours: The Microbiology

1. ***What is an odour?*** As Patrick Süskind put it so well, "our language is worthless to describe the world of smells". However, we are going to try to decipher this complex and subtle world of smells, and in particular the microbial origin of some of them. What is a smell? **The odour we smell is generated by one or more molecules with special chemical properties: the small size and hydrophobic (fatty) nature of these molecules called "volatile" compounds allows them to be transported by air.** Some of these volatile compounds are recognised by sensory cells in our nostrils, so that we detect a particular smell, which can be pleasant or unpleasant, and which therefore **carries information**: in the example of the refrigerator mentioned above, the mother, alerted by her child, will identify the decomposing fish as the source of the bad smell. This smell serves as a signal to human beings - and to animals, whose sense of smell is often much more developed than ours - and is a warning not to eat food that gives off such a smell. On the other hand, the smell of cheese - which can also be strong - in the same refrigerator will trigger a completely different reaction. We are therefore able to discriminate between the information conveyed by these two types of odours and adapt our behaviour accordingly. **Why do fish and cheese smell so different?** To answer this question, we first need to understand where the smells of these foods come from…

2. ***Many odours come from the activity of bacteria.*** When we imagine smells, we may think of the scent of flowers, the smell of the forest or of freshly cut grass. All these smells produced by plants have a special biological function, for example to attract pollinating insects or to warn neighbouring plants of imminent danger so that they can defend themselves. What about the fish or cheese in our refrigerator? Here, unlike in plants, **the odours are no longer those of the living animal (fish) or the basic product (milk), but come from the activity of bacteria that feed on and process these foods.** In the case of fish, the very strong smell comes from the decomposition of the animal's proteins. Bacteria use these proteins as a food source and ferment them, releasing toxic substances and volatile compounds with a very strong odour that the animals and we have learned to detect to avoid poisoning ourselves with spoiled food. As for cheese, it is also a product that has been transformed by the action of bacteria, but here milk sugars, not proteins, are used as a food source. This bacterial fermentation process that transforms milk into cheese makes this product edible for us and therefore carries an odour that we associate with good food. It should be noted here that **the same odour can be repulsive to one organism, but attractive to another**: we find the smell of decomposed fish, for example, very unpleasant, but the same odour will be attractive to flies and serve them as a guide to find the source of food. This difference in perception is valid for many smells generated by bacterial activity, from compost to manure and cow dung: so many smells that we find unpleasant but which attract flies and other insects that feed on this vegetable or animal waste. Thereby, they participate in the tireless work of the bacteria that play the role of rubbish collectors and waste recyclers on our planet. This essential bacterial work enables plants, which are at the base of our entire food chain, to find in the soil the nutrients they need to grow. **Bacteria are therefore real allies for plants** and the two types of organisms maintain a **mutually beneficial relationship, in which bacterial odours play a major role**.

3. ***Bacterial odours stimulate plant growth.*** At first glance, it seems strange to think that plants can detect bacterial odours, as they have no nose to smell them! However, flies do not have a nose either, and yet they use these volatile signals to find their food, as we have just seen. We must therefore believe that smells can enter the body of insects through other means than the

nose, and we now know that **plants too can integrate these small molecules into their roots and leaves, and adapt their behaviour accordingly, for example by increasing their growth**.

To understand the role of these bacterial odours in the relationship between the plant and the bacteria, we must first know that in nature, plants do not live alone, but are colonised by many beneficial bacteria, which live in the surrounding soil, in their roots or even on their leaves. These bacteria, unlike the example of fish mentioned above, do not degrade plants but live off the excess food that the plant produces through photosynthesis. In exchange, **bacteria emit volatile compounds that help the plant acquire what it cannot make itself, i.e. mineral elements.** For example, iron is usually present in soil in insoluble form and bacterial volatiles can make it more soluble and hence increase its availability to plants. Likewise, plants can take up sulfur-containing volatiles emitted by bacteria and use them as sulfur sources for their growth. Moreover, some bacterial odours also act as **natural growth hormones** and indicate to the plant that it should produce more roots (Figure 1). This root proliferation benefits the plant, which will grow better and be more able to **withstand drought and other environmental stresses**, but it also benefits the bacteria, because the plant feeds its bacterial inhabitants through the roots by secreting organic molecules produced by photosynthesis and which most bacteria need.

Figure 1: Bacteria living in the soil and on the leaves emit volatile compounds that are beneficial to plant growth. Illustration by Viviane Perraudin.

4. ***Bacterial odours protect plant health.*** While a wide range of bacteria are beneficial to plants, other bacteria and many fungi, commonly known as pathogens, threaten plant health. These pathogenic organisms cause diseases that weaken plants and can even kill them in some cases. This poses serious problems when it comes to century-old trees or agricultural crops that are necessary to feed the human population. Yet plants are not defenceless; like us, they have an immune system that helps them to fight diseases. However, **certain smells emitted by beneficial bacteria living in the roots, the surrounding soil, or on the aerial parts of plants, can stimulate the plants' immune system and warn them of a potential danger**. This allows the plant to prepare itself in advance and defend itself more effectively when attacked by a pathogenic fungus.

In addition to stimulating the plant's immune system, bacterial odours also have other, more direct and powerful ways of protecting plants from their enemies: **some of these odours are**

real chemical weapons, which, although they do not affect plants, are highly toxic to their enemies. Bacteria, which receive shelter and food from plants, can therefore also act as little soldiers ready to defend their host plant by emitting specific smells that will repel approaching plant enemies (Figure 2).

Figure 2: Bacteria living in the soil emit volatile compounds that help the plant defend itself against pathogenic organisms. Illustration by Viviane Perraudin.

5. ***Bacterial odours as a means of long-distance communication.*** For us human beings, communication is mostly verbal or gestural. We also understand our pets by the noises they make or by their behaviour. Yet beyond these two forms of expression, many other means of communication have existed between living beings since the beginning of evolution. The **language of chemistry**, i.e. the exchange of chemical signals, **is without doubt the ancestral and most commonly used means of communication throughout the different kingdoms of the living world**. Bacteria have developed a whole language of chemical communication that enables them to interact with each other, with plants and with animals. Within this extended vocabulary, odours - and in the broader sense volatile compounds - have a particular property: **they can be emitted and "heard" or perceived at a greater distance** than non-volatile compounds. It is very useful for us to be able to detect whether a food is still edible or not before putting it in our mouths. Similarly, it is much more effective to protect a plant by repelling its enemies before they reach it, which is only possible with volatile compounds. **The action of these odours is therefore broader than that of other chemical signals that are not volatile**. In some environments, plants are distant from each other and the aerial or root parts of the soil, made up of soil particles, are separated by air. The emission of volatile compounds is usually the only way to reach other organisms that share the same environment without being physically linked to each other.

6. ***How can bacterial odours be used to preserve the environment?*** As we have seen, bacterial odours improve plant growth (increasing root growth and biomass in general), resistance against various stresses, such as drought or salinity, and resistance against diseases. All these properties are of **great agronomic and ecological importance**. Indeed, to increase plant growth,

we still often resort to mineral fertilisers, the production of which causes the emission of greenhouse gases and pollutes our water and soil. To protect crops against diseases, agriculture uses plant protection products, which most of the time are either synthetic molecules that are difficult to degrade biologically and often have harmful effects on the environment and human health, or metals such as copper that accumulate in the soil and disrupt the life of fauna and microflora. **In this sense, replacing at least some of these products with alternatives based on the use of compounds naturally emitted by bacteria, and which act at a great distance due to their volatile nature, seems a promising approach to protect the health of the environment and of future generations**.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 2: Zero Hunger:** *End hunger, achieve food security and improved nutrition and promote sustainable agriculture.* Microorganisms are naturally present in soils. The volatile compounds produced by these microorganisms can promote plant root growth, allowing them to draw more water and nutrients. As a result, plants will produce more leaves, flowers or fruit and will be more resilient to environmental stresses such as drought. Maintaining and stimulating microbial life - and thus the production of volatile compounds - can contribute to less input-intensive and more sustainable food production.
- **Goal 3: Good health and well-being:** *Ensure healthy lives and promote well-being for all at all ages*. The massive use of pesticides in agricultural production poses a serious health risk to all. When crops are treated with pesticides, a certain amount of the pesticide will reach and potentially stick to the edible parts of the crop, and some of them can be absorbed and carried by the plant. As a result, consumers who eat these foods also ingest pesticide residues, even if they have taken the trouble to wash the food. Replacing pesticides with bacterial volatile compounds would reduce pesticide residues on food, since volatile compounds, due to their chemical properties, would be less likely to be deposited on food and remain attached to it.
- **Goal 6: Clean water and sanitation:** *Ensure availability and sustainable management of water and sanitation for all.* Another consequence of the massive use of pesticides is the accumulation of pesticide residues in the soil. During heavy rainfall, they are transported by rainwater to groundwater, rivers, and lakes. These residues can then also be found in the running water that comes out of the taps in our homes. Volatile compounds will be less likely to accumulate in the soil and will also not be carried away - or very little - by rainwater. Repeated exposure to cocktails of pesticide residues carried by drinking water puts our health at risk. Replacing these pesticides with volatile compounds or with bacteria that produce volatile compounds would prevent the accumulation of pesticide residues in soils and their passage into drinking water.
- **Goal 12: Responsible consumption and production:** *Ensure sustainable consumption and production patterns.* The world's population continues to grow, and with it the pressure to produce more food while the available arable land does not increase. Currently, the production of raw materials and food is mainly based on the massive use of fertilizers and pesticides. An alternative solution could be the use of volatile bacterial compounds, which have both fertilizer properties (stimulating plant growth) and pesticide properties (controlling plant enemies and stimulating the natural defences of plants). Bacterial volatile compounds are therefore an interesting alternative to fertilizers and pesticides, as they are more environmentally friendly.
- **Objective 13**: **Climate action:** *Take urgent action to combat climate change and its impacts.* The carbon footprint of the production of synthetic nitrogen fertilizers for agriculture represents 1.2% of the CO_2 emitted by human activity. In addition, the use of these fertilizers also generates the emission of nitrous oxide (N_2O), a greenhouse gas that contributes to global warming and the

deterioration of our planet's ozone layer. Chemical fertilizers are also a source of pollution for streams, rivers, and lakes when applied excessively or at the wrong time. The accumulation of nutrients in the water can lead to a massive proliferation of algae that will asphyxiate aquatic ecosystems, a phenomenon called eutrophication. Some volatile compounds produced by soil bacteria could be used as an alternative to chemical fertilizers. These compounds are naturally produced by soil bacteria and not chemically synthesized. Therefore, replacing at least part of the fertilizers with bacterial volatiles would reduce the carbon footprint of agriculture, as well as the emission of greenhouse gases.

- **Objective 15: Life on land:** *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.* Using bacteria and their volatiles as alternative to pesticides indirectly contributes to maintaining environmental health, since these crop protection strategies will be less harmful to bees and other organisms providing key ecosystem services. Moreover, a soil free of bacteria, fungi and other microorganisms is a soil devoid of plants, which then becomes very susceptible to erosion by wind and rain, and consequently to desertification. By being anchored in the soil, plants' root systems hold the soil in place, and plant stems and leaves cover its surface. In this way, they protect the soil against torrential rains and strong winds that would gradually degrade bare soil. Soil microorganisms act as tiny farm workers and are largely responsible for supplying the soil with nutrients. Bacterial volatiles play an essential role, because by diffusing between soil particles, they regulate the short- and long-distance interactions between the different microorganisms living in the soil and ensure communication between microorganisms and plants.

Potential Implications for Decisions

1. *Individual*

a. Health protection. Paying attention to food odours before eating to detect possible contaminations by microorganisms can help protect your health and the health of those around you.

b. Consumer's choice. Environmentally friendly agriculture promotes microbial activity in the soil, including the emission of bacterial volatiles that stimulate growth and protect plant health. Eating food produced in this way helps to protect the environment and to support sustainable development objectives.

c. Maintenance of private grounds. In addition to professional agriculture, the maintenance of green areas and private gardens also contributes significantly to environmental pollution: opting for organic fertilisers (e.g. compost), maintaining soil cover and not using pesticides in one's garden is a local contribution to preserve human and environmental health on a global scale.

2. *By distribution companies*

a. Adapting the product offer in shops. The consumer's purchase of food obtained from more or less sustainable production will depend heavily on the choice offered to him by the distribution and sales companies. Opting for an increased supply of sustainably produced products and for competitive prices for these products is an effective way to promote human and environmental health.

b. Informing consumers on how food and other goods are produced. To enable consumers to make an informed choice of products, information on production methods as well as on energy demand and environmental impact should be given in a clear and transparent manner.

3. By public communities and authorities

a. Maintenance of public grounds. By maintaining their numerous grounds, parks and gardens in such a way as to preserve soil microbial life, public authorities can make an important contribution to the reduction of pesticide residues in soil and water and improve human health while protecting the environment.

b. Funding of research. Many scientific and technical developments in the field of agriculture have been financed or co-financed by companies producing fertilisers and pesticides. In order to promote the practical application and exploitation of the potential of microorganisms and their volatile compounds to improve the sustainability of agriculture, funding for research in this field needs to be provided.

c. Adjustment of legal provisions related to the authorisation of use for new products. Before bacterial volatiles or the bacteria that produce them can be applied as alternatives to fertilisers and pesticides, studies on the impact of these new products must be carried out, which serve as a basis for authorising their use. At present, this registration process is very costly, preventing many promising compounds and organisms from finding their way into practice. Improving the legal framework governing these applications for authorisation to facilitate and speed up the process is an important step towards more sustainable agriculture.

Pupil participation

1. Class discussions

a. Discussion of the nature and origin of different odours linked to microbial activity (sauerkraut, yoghurt, cheese, soil, compost, manure, but also spoiled food).

2. Pupil stakeholder awareness

a. Reflection on the advantages and disadvantages of the use of volatiles emitted by bacteria in agriculture. Discussion on how to overcome the disadvantages inherent to the use of bacterial volatiles.

b. Reflection on what everyone can do personally to promote sustainable development by taking advantage of bacteria and their volatile compounds.

The Evidence Base, Further Reading and Teaching Aids

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Glossary

Molecules: several atoms linked together by chemical bonds to form a stable compound.
Hydrophobic: not miscible in water.
Bacteria: microscopic unicellular organisms.
Proteins: large molecules made up of several amino acid units linked by peptide bonds.
Fermentation: metabolic process allowing, in the absence of oxygen, to transform a food source into energy.
Photosynthesis: the process by which plants, algae and certain bacteria use the sun's energy to produce organic substances from carbon dioxide present in the atmosphere.
Pathogen: an organism capable of causing disease in other organisms.
Greenhouse effect: a natural phenomenon by which the atmosphere filters and retains a certain amount of light radiation that is captured by the earth's surface and released as heat, thereby maintaining an optimal temperature for the survival of species.
Greenhouse gases: gases that increase the capacity of the atmosphere to trap the earth's radiation, leading to a warming of the earth's temperature and consequent climate change.