A child-centric microbiology education framework

Let's go to the beach!
The Wonderful Smell of the Sea

Daddy: I can smell the sea!
We must be close to the coast now: can we go for a swim tomorrow?

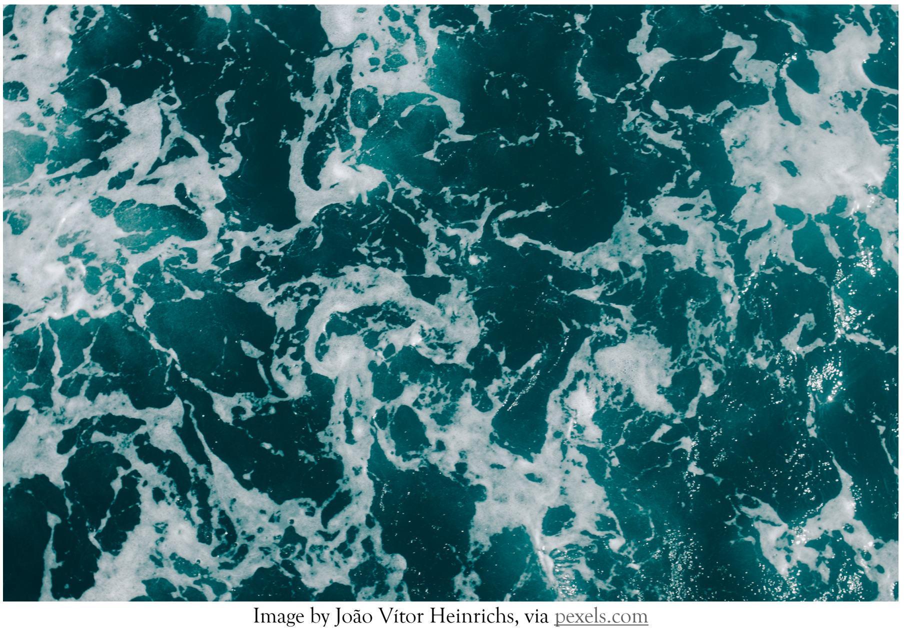
Image by João Vítor Heinrichs, via pexels.com

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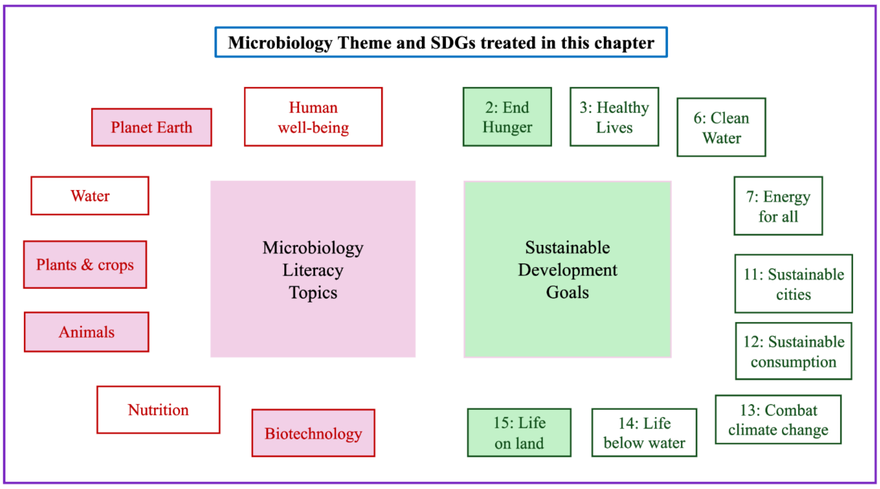
The Smell of the Sea

Storyline

Dimethylsulfide or DMS is a smelly sulfur gas that is produced in large amounts by microorganisms in the sea, and it is because of this marine association that it is sometimes thought of as the *smell of the sea*. However, it is much more than that. In fact, this compound is significant in a wide range of aspects of the biosphere and the earth system; it even has meaning in our daily lives. The most recognised environmental role of DMS is that it is a source for atmospheric particles. As such, DMS affects the heat balance of the atmosphere and the formation of clouds. DMS is also transported from the oceans to the terrestrial continents via the atmosphere where it helps to replenish sulfur stocks in soils, thereby supporting healthy plant growth and agriculture. Fascinatingly, some seabirds use the smell of DMS to find feeding areas in the vast oceans. The activities of unseen microorganisms are instrumental in the production and degradation of DMS and are vital to cycling of this compound. And, perhaps surprisingly, most of us smell DMS daily, such as when we prepare and eat food.



The Microbiology and Societal Context

The microbiology: DMS production and consumption by microorganisms; DMS metabolism. *Sustainability issues*: health; food and energy; environmental pollution; climate. DMS is a very smelly compound, the stench of DMS in its pure form and at high concentration is unbearable, however, at very low concentrations, DMS can impart pleasant characteristics to the odour and aroma of foodstuffs and beverages. At elevated concentrations, we may experience it as unpleasant off odours, for instance emissions from wastewater treatment or the processing of solid waste may also generate DMS and related volatile sulfur compounds. In the atmosphere, DMS is converted to aerosols that have a cooling effect on our climate potentially offsetting some of the effects of greenhouse gasses.

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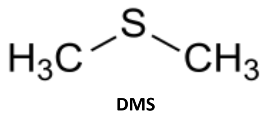
The Smell of the Sea: the Microbiology

1. ***What is the smell of the sea?*** Have you been at the seaside? Have you noticed any specific smells? If you normally live inland, it is likely that the fresh air at the seaside smells different from fresh air inland. Some of these differences are due to the production of volatile compounds that get into the air. Because the type of smelly chemicals can vary depending on where we are, inland, at the coast, or even on the sea, we may associate them with specific places. Many organisms living by or in the sea produce compounds that have characteristic smells and some people suggest that there is a specific *smell of the sea*. Most often, this refers to a compound called dimethylsulfide – abbreviated as DMS – but DMS is by no means the only smelly chemical originating in the marine environment.

2. ***Dimethylsulfide (DMS) is an organosulfur compound and a lot of it is produced in marine environments.*** Chemically speaking, DMS is an organosulfur compound. The chemical structure of DMS is shown here.

A



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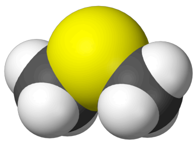


C

$(CH_3)_2S$

Structure and formula of dimethylsulfide. (A) Structural formula, (B) space filling model or calotte model, (C) elemental formula. Source Panel B: Wikimedia

DMS is a liquid at room temperature but, due to its low boiling point of 37°C, it evaporates quickly to become a gas. Liquids (and solids, for that matter) that evaporate at low temperature are called volatile compounds. When they become gases they can enter our noses and, if they have an odour, we smell them immediately. Noses are built to detect volatiles. Sulfur compounds are often volatile and smelly, just think of the horrible smell of bad eggs – hydrogen sulfide. Because of its strong tendency to volatilise, DMS is sometimes referred to as a sulfur gas.

3. ***Most DMS is is formed from DMSP.*** DMS occurs naturally in the environment as a biogenically-produced compound, a compound produced by living organisms. Although there are many ways in which DMS is produced in nature, most DMS is produced by decay of another sulfur chemical called dimethylsulfoniopropionate, or DMSP, which is present in a wide range of microorganisms in the marine environment, including micro- and macroalgae (e.g. seaweeds), bacteria, the organisms that are symbiotic with corals, and even specific grasses in saltmarshes. These organisms can contain large amounts of DMSP inside their cells.

DMSP is a very important protective compound with a diversity of cellular functions, including

- Osmoprotection: salt levels in marine and coastal systems can vary – just think of water evaporating in rock pools during which salt concentrates – and this is very stressful for single celled organisms lacking a protective skin, because high salt tends to pull water out of the cell. This is lethal for cells, so they prevent this by producing compounds like DMSP, a powerful osmoprotectant, which prevent this.
- Antioxidant: marine organisms living in surface waters are exposed to high levels of sunlight, which causes the production of oxygen radicals that are very dangerous and

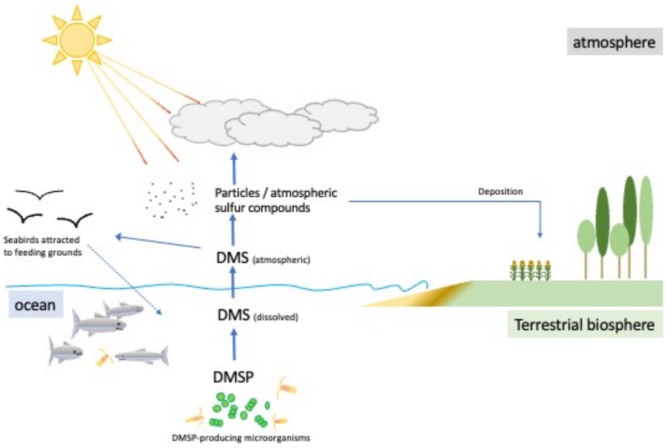
damage internal metabolites and cell structures. DMSP is an antioxidant that scavenges oxygen radicals and other dangerous products and so protects the cell.

- Cryoprotectant: organisms lacking the temperature control systems that we have must deal with temperature fluctuations in a different way. DMSP protects internal cellular molecules from freezing when temperatures fall below 0°C.

When organisms die, their cellular contents, which include DMSP, leak out into the environment. For instance, when tiny zooplankton eat microscopic algae containing DMSP, they release DMSP into the seawater where it becomes available to marine bacteria which convert it to DMS. You may be surprised to know that there are about 1 million bacteria in each millilitre of seawater, and many of these can degrade DMSP, making DMS in the process.

4. **Emission of DMS from the ocean into the atmosphere has a number of important environmental consequences.** When DMS is produced in the ocean surface or in saltmarshes it becomes airborne with various environmental consequences (see image below for an overview). In the air it is chemically converted to other sulfur compounds including methanesulfonic acid (MSA) and sulfate, which can form atmospheric particles (aerosols). These aerosols serve as cloud condensation nuclei by binding water into droplets which essentially contributes to the formation of atmospheric haze and clouds. Aerosol, haze, and clouds reduce the amount of sunlight and heat radiation reaching the Earth's surface, and thus have a cooling effect on the atmosphere and potentially affect global temperatures and climate. The potential of atmospheric DMS to reduce surface temperatures is of great interest since the global average temperatures are increasing as a consequence of climate change.

Another important aspect of microbial production of DMS is that some of the sulfur formed from DMS in the atmosphere is also transported back to the terrestrial environment where it is deposited on soils. All organisms, plants included require sulfur as an important building block for biosynthesis, especially in the form of sulfur containing amino acids such as methionine and cysteine. Some soils may contain only low concentrations of sulfur that is available to plants, so atmospheric deposition of sulfur derived from DMS on soils increases plant growth.



Environmental interactions of DMS. DMS emitted into the atmosphere leads to formation of particles that bind water and that contribute to cloud formation. Clouds, as well as aerosols block out some of the sunlight and heat radiation coming into the atmosphere, providing a cooling effect. Sulfur aerosols also become deposited in the terrestrial biosphere, fertilising soils. DMS in the atmosphere attracts seabirds to areas of high productivity ensuring seabirds can locate areas with higher fish abundance. Schematic by Hendrik Schäfer and Willem Schäfer

DMS and the precursor compound DMSP also play important roles in the food web of the ocean which extends all the way to attracting sea birds to biologically-productive feeding grounds. The latter is based on the interaction between phytoplankton (microscopic algae) which contain DMSP. Marine phytoplankton are an important component of the marine foodweb, forming the basis for higher organisms that consume them. Copepods are small predatory crustaceans that feed on phytoplankton. When copepods feed on DMSP-containing phytoplankton, the intracellular DMSP from the algae is either released into the seawater due to the sloppy feeding of the copepods, or it is ingested by the copepods; either way it will be degraded by bacteria in seawater or in the copepods' digestive system, releasing DMS. DMS emitted into the atmosphere from areas of high productivity can be sensed by seabirds which use this to locate suitable feeding grounds in the vast area above the ocean. Since copepods are a key prey for fish, this ultimately leads the birds which feed on fish to areas where they find their prey.

5. **Microorganisms can grow using DMS as a food source or use it to derive energy which removes DMS from the environment.** It has been estimated that approximately 80-90% of all the DMS produced in the surface ocean is actually not emitted into the atmosphere but degraded by microorganisms. Nevertheless, a large amount of DMS, representing approximately 28 Tg of sulfur, is emitted to the atmosphere annually. DMS emissions from seawater would potentially be much higher if it was not for microorganisms that utilise DMS as a food source.

All microorganisms require food and energy to survive. Although the actual concentrations of DMS in the environment are usually quite low (typically low nanomolar), there are bacteria that can use DMS at such concentrations as a food source. Examples of bacteria that can grow on DMS in the presence of oxygen (aerobic microorganisms) include several species of the genera *Hyphomicrobium* and *Methylophaga*. The fate of the sulfur of DMS is dependent on the species of bacteria. Some bacteria produce sulfuric acid, others produce thiosulfate or polythionates. When oxygen is not available, DMS can be converted by methanogenic microorganisms to methane (CH_4), which is a potent greenhouse gas.

6. **Yes, the sea sometimes *really* smells of DMS and so do a number of other things we experience every day.** There is probably always a small amount of DMS in the marine atmosphere and it therefore depends on how sensitive your nose is for DMS. Pure DMS has a terrible smell (even stench). On a visit to the North Sea coast I once experienced that the sea definitely smelled of DMS; my son even found the smell quite strong. Standing on the beach and looking onto the water, I noticed a surface slick on the water which turned out to be due to a bloom of microscopic algae called *Phaeocystis*. These algae grow in little gel-like colonies and produce huge amounts of DMSP, and hence DMS is likely to be released into the water and air. Saltmarshes can also have a lot of DMSP production and consequently smell of DMS sometimes.

Left panel, a water sample taken on the North Sea coast on the island of Spiekeroog in Germany in June 2018, when the sea smelled of DMS due to the bloom of *Phaeocystis* algae, which can be seen floating in the bottle. **Right panel**, Stiffkey salt marsh in Norfolk (UK), where *Spartina anglica* grass is widespread, a plant that produces the DMS precursor DMSP (note, *Spartina* is now reclassified as *Sporobolus*). Figure 3 photos by Hendrik Schäfer

Perhaps surprisingly, although it is often referred to as the *smell of the sea*, DMS is a compound that most of us may experience daily. For instance, DMS contributes to the complex aroma and taste of many common foodstuffs (some when cooked) and beverages. Although DMS may not be the main characteristic component, it will be part of their aroma and smell. A few notable examples include honey, coffee, malt, cabbages, raspberries, processed tomato products, beer and UHT milk. That sweetish smell you get when opening a tin of sweetcorn also contains DMS.

As mentioned earlier, at high concentrations DMS has a disagreeable smell and can therefore be responsible for unpleasant odours. Some of the foods we eat contain compounds that can be converted to DMS by microorganisms in our gut, and so DMS is also produced in our gut and be noticeable when someone passes wind (!). At a larger scale, DMS can also be a nuisance odour associated with wastewater treatment plants, which have been shown to contain active microbes that both produce and degrade DMS.

There is also a rare genetic condition which leads to a malfunction of organic sulfur metabolism in humans, resulting in increased levels of DMS in the breath of affected individuals, who therefore suffer from bad breath caused by exhaling DMS from via their lungs. This is known as extra-oral halitosis (the medical term for 'bad breath') and is detrimental to those who suffer from it. Because this form of bad breath is not due to poor dental hygiene, no amount of brushing one's teeth will help to alleviate it.

As you can see, microorganisms are essential in driving many of these globally important transformations of DMS and play an important role in its cycling.. For a long time, the atmospheric and climatic effects of DMS have been the main motivation for research on DMS-cycling microorganisms, but we are becoming increasingly aware of related aspects of microbial DMS cycling that may be important for ecological interactions and may even have relevance for human health.

Suggested learning activities

- Highlight any words of whose meaning you do not know and make a glossary
- Find out more about the properties of DMS using Wikipedia or the PubChem database
- How much is the annual emission of DMS per m^2, km^2 of ocean surface in grams? Students will need to find information about the area of the global ocean surface and calculate accordingly.
- If DMS emitted from the ocean per year is 28 Tg of sulfur, what is the corresponding mass of DMS emitted from the ocean?
- Advanced: what is the volume of liquid DMS that is emitted.? What information would you require to convert mass to volume?
- Discuss the meanings of the terms volatile, biogenic compound, radiative forcing, and greenhouse gas

Glossary

Con formato: Inglés (americano)

Dimethylsulfide (DMS) – A sulfur-containing compound with a strong smell, often linked to the sea.

DMSP – A sulfur compound produced by marine organisms that can be converted into DMS.

Microorganisms – Tiny living organisms such as bacteria and algae.

Volatile compound – A substance that evaporates easily into the air.

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Organosulfur compound – A chemical compound containing sulfur and carbon.

Aerosol – Tiny particles suspended in the atmosphere.

Cloud condensation nuclei – Small particles that help water droplets form clouds.

Biogenic – Produced by living organisms.

Osmoprotection – Protection of cells against changes in salt concentration.

Antioxidant – A substance that protects cells from damage caused by oxygen radicals.

Cryoprotectant – A substance that protects cells from freezing damage.

Phytoplankton – Microscopic algae living in oceans and other waters.

Methane – A greenhouse gas produced by some microorganisms.

Greenhouse gas – A gas that traps heat in the atmosphere.

Radiative forcing – A process that changes the balance of heat entering and leaving Earth's atmosphere.