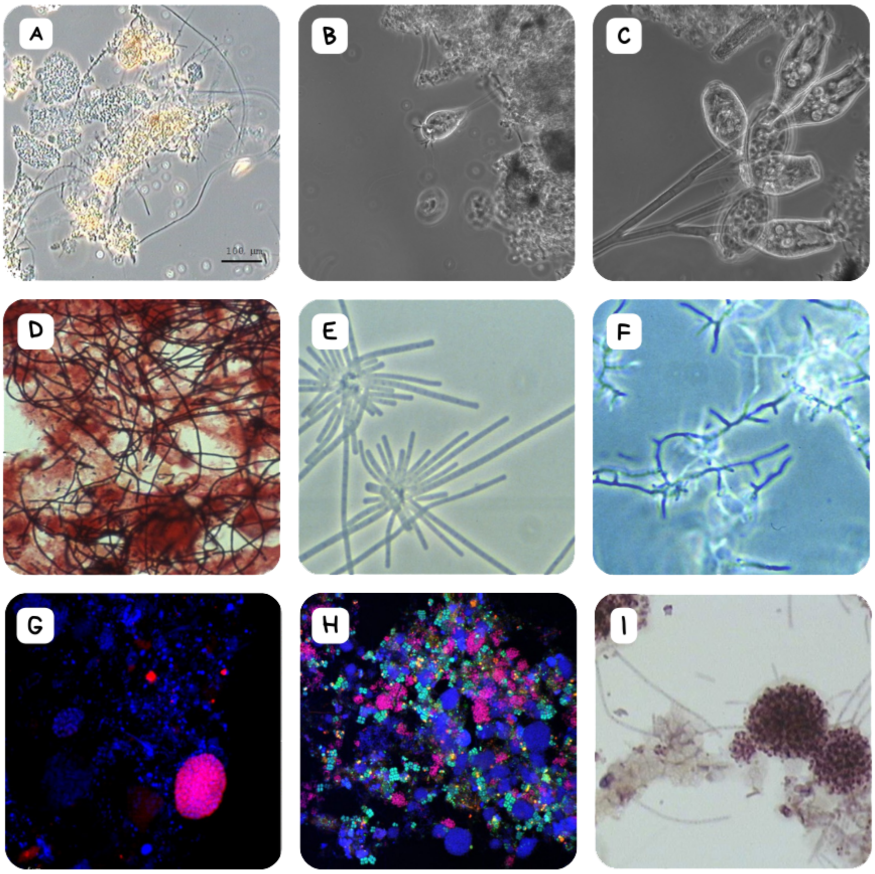
Life in wastewater treatment plants: microbes are our invisible friends

Mummy what happens to poo when it is flushed away?



Microbes live in wastewater treatment plants where they transform the urine and feces into clean water which is released in rivers and lakes or reused in agriculture or for industrial applications. Look closer using a microscope and you will see small microbial aggregates made of single cells called "flocs" **A.** You will also see protozoans freely swimming or attached to the flocs **B-C**. They eat the free-living bacteria and thereby contribute to the production of a good quality effluent. Different amazing filamentous bacteria can be also found in activated sludge **D-F**. They participate to the wastewater purification and may serve as a "backbone" to floc structure, allowing the formation of larger and stronger flocs. What are microbes doing for us? They efficiently remove organic pollutants, nutrients and, importantly, kill off many pathogenic microbes. Look at nitrifiers (small colonies in pink color) **G,** and at the round clusters of PAOs within the activated sludge flocs (in pink color) **H,** with dark granules of polyphosphate inside the cells **I.**

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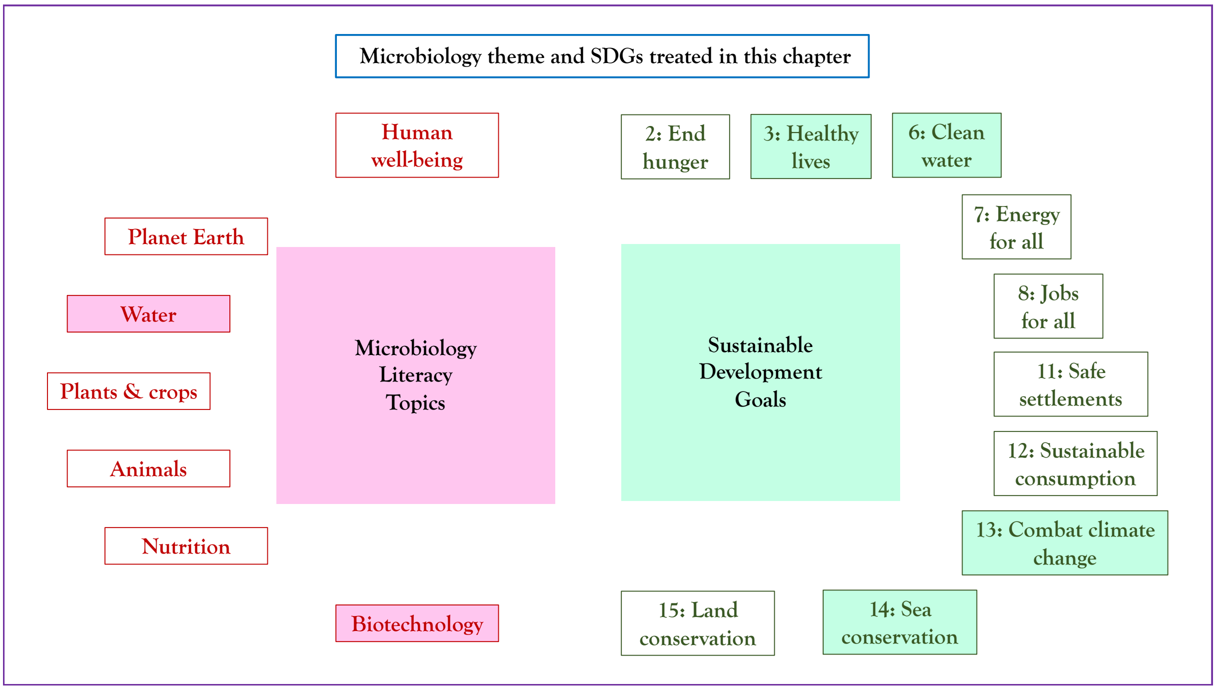
Life in wastewater treatment plants: microbes are our invisible friends

Storyline

All living beings produce waste. Ordinarily, this waste is rapidly degraded and recycled where it is produced by microbes. However, humans are different from other beings. They mostly live in large communities that produce huge amounts of waste that cannot be degraded as fast as it is produced, so it would accumulate and form massive waste mountains if we had no mechanism to deal with it. Humans are also special beings in that they create massive amounts of "unnatural" waste, like packaging, toys, household machines and toxic chemicals, all of which can pollute the environment. To deal with human wastes, we have created landfills for solid wastes, and wastewater treatment systems to deal with liquid wastes. Wastewater treatment systems not only dispose of waste materials but also remove harmful components, like pathogenic microbes and toxic chemicals, both of which can cause disease, so they are vital to our wellbeing. Wastewater treatment is a wonderful example of the essential practice of recycling. It involves degradation of our organic waste but also the conversion of some of it into biogas, an important source of energy, and the recovery of clean water, nitrogen and phosphorus, which are all valuable components of wastewater.

The Microbiology and Societal Context

The Microbiology: pathogen removal; biodegradation of water contaminants; nutrients recovery; water-borne diseases prevention; biofilms; clean water production. *Sustainability Issues*: good sanitation and health for humans and environment; pollution prevention; treated wastewater reuse; aquifer recharge; wastewater as a resource; energy and resource recovery; circular economy.



Life in wastewater treatment plants: The Microbiology

1. ***A brief history.*** The need to purify water and maintain hygiene through wastewater collection and treatment, which mediates removal of the organic matter, viruses, bacteria and parasites, was already apparent in very ancient times. The wastewater treatment process used today thus evolved over many thousands of years. Around 4000 B.C., the Mesopotamians started to connect homes to drainage systems that could carry away wastewaters from the point where they were produced. Almost 1000 years later, the first Indus civilization developed the first system that had a form of treatment. But it was only during the Roman Empire that wastewater disposal into rivers was engineered and became systematic. Cloaca Maxima in Rome is one of the earliest sewage collecting systems. During this period, all households were connected to the sewage collection system which was expansive with many small channels that flowed by gravity to larger channels. They also had separate networks for fresh water (aqueducts) and wastewater (sewers) transport, as they realized the need to avoid a proximity of fresh water sources to wastewater discharge points, in order to avoid illness and epidemics. More than 2,500 years later, parts of these systems are still in operation today.

Only in the 19th century, with advances in microbiology and the invention of the microscope by Antoni van Leeuwenhoek, did many scientists like Robert Koch and Louis Pasteur figure out that the harmful bacteria in the wastewater were causing cholera and other illnesses. Authorities, particularly in the United Kingdom and USA, began to recognize the need for wastewater treatment, realizing that removing pollutants is essential before releasing it into the environment. Thus, various studies were undertaken, and methods were developed to treat wastewater. More stringent laws were passed for better waste disposal practices.

Humankind is a huge consumer of freshwater which is used for various purposes, such as drinking, cooking, washing, and diverse industrial processes and, in the process, is converted to "used" or "wastewater". In most countries today, wastewater from essentially all buildings and facilities that receive freshwater is collected in networks of sewers that channel it to wastewater treatment plants where it is treated to remove the contaminants that were introduced during usage of the freshwater. There are different types of wastewater treatment plant that use different types of technology. However, the most common and effective plants are based on the activated sludge process.

2. ***Activated sludge.*** In 1913, the activated sludge treatment process was discovered in the UK by two engineers, Edward Ardern and W.T. Lockett. They found that the "*solid matter obtained by prolonged aeration of sewage, which has been termed activated sludge, has the property of enormously increasing the purification affected by simple aeration of sewage*". Nowadays, the sanitation facilities, toilets, and treatment solutions help to efficiently produce clean water from sewage, allowing sanitation and preserving the health of humans and environment.

Let us go through the magic world of "activated sludge" and discover how microbes are useful for all living beings thanks to their incredibly amazing role in cleaning wastewater, allowing its reuse and keeping healthy and safe the environment where we live!

3. ***What is sewage and why do we need to purify it?*** Sewage is liquid waste matter (named simply as wastewater) containing feces, urine and dirty water produced in our homes, workplaces, factories and industries which flows away from the sites of production through sewers towards a treatment plant. There it is transformed into clean water thanks to the action of invisible friends called bacteria. Wastewater is a complex mixture containing suspended solids, organic and inorganic impurities, nutrients, disease-causing bacteria, and other microbes. In most countries it includes rainwater running down the streets during a storm or heavy rain. The water that

washes off roads and rooftops may carry harmful substances with it. When wastewater is discharged untreated into rivers or seas, it pollutes receiving waters which become dangerous for humans, aquatic plants and animals. Without appropriate treatment, the organic matter and nutrients (nitrogen and phosphorus compounds from soaps, detergents and fertilizers etc.) enter lakes, rivers and marine coastal areas and become a food source for microorganisms growing by using the dissolved oxygen of the receiving water body. The more pollutants are released into water, the greater the likelihood of uncontrolled microbial growth and formation of algal "blooms" – eutrophication – that cause undesirable ecological effects. One of the most important of these is a high consumption of oxygen caused by the blooms and the creation of oxygen-minimum zones in which oxygen-requiring organisms like fish die off.

4. ***Poo is not just organic matter and nutrients: it is also a rich source of pathogens.*** The feces of a healthy person contain large numbers of microbes – about a billion cells per gram of feces –most but not all of which are relatively harmless. However, people with an intestinal infection, for example causing diarrhea, may also excrete huge numbers of disease-causing viruses, bacteria or other intestinal parasites. Such pathogens occurring in untreated wastewater can contaminate clean water sources causing serious waterborne diseases and sometimes deadly illnesses to humans and the other living beings. This is a major public health concern which requires rapid and reliable detection methods to efficiently prevent human exposure.

5. The need to monitor wastewater and wastewater treatment process effluents: the importance of proxies. Because the pollutants and pathogens in wastewater represent a major hazard, to protect people from harm it is essential to monitor them in the treated waters released from the wastewater treatment plant into rivers and lakes. Ideally, monitoring procedures would target specific hazardous components. Even though there is an increasing interest and great efforts for the development and application of advanced biomolecular tools for the rapid and specific detection of waterborne pathogens in (waste)water, in practice, sewage is so complex and variable that it is not possible to monitor most substances it contains. Therefore, we rely on "proxies" of contamination, markers that indicate the likely presence of a contaminant. For example, indicators of fecal pollution continue to be a valuable proxy for fecal pathogen loads that allow assessment of water quality and the related potential health risks. *Escherichia coli* and enterococci are often used as fecal indicator bacteria and coliphages and bacteriophages are often adopted as fecal indicator viruses.

6. Monitoring organic matter levels. There are also useful parameters commonly utilized in wastewater treatment that can help us to determine the biodegradability of sewage. The first one is the five-days Biochemical Oxygen demand (BOD_5). This test indicates the degree of water pollution with biodegradable organic matter and measures the oxygen consumed by microorganisms as they utilize (oxidize) the soluble organic matter in the wastewater for their growth. The test measures only the approximate amount of oxygen that will be required by a sewage when it is exposed to oxygen for an extended period.

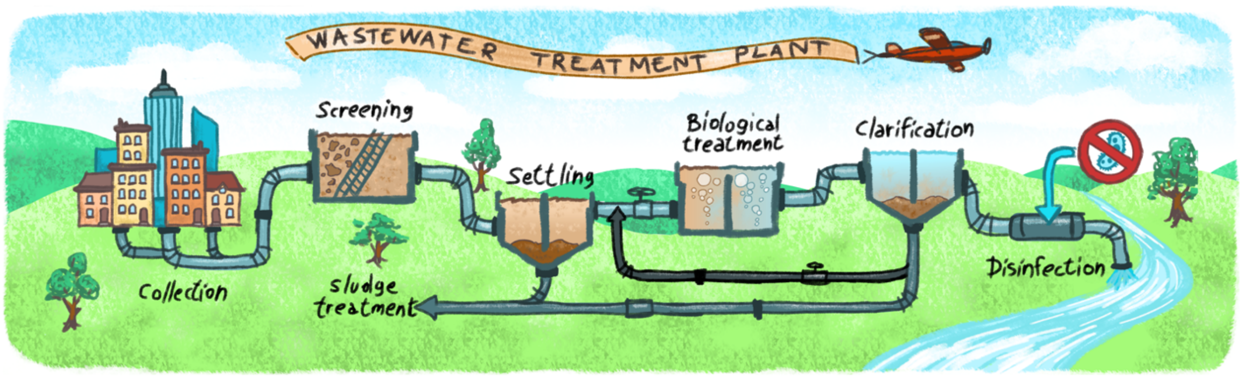
However, toxic substances in the wastewater might inhibit or even prevent bacterial growth and, therefore, oxidation of the organic matter. When this happens, the test result is lower than the actual amount of organic matter present would suggest. For this reason, a second parameter, the Chemical Oxygen Demand (COD), is evaluated. It measures the oxygen consumption resulting from the chemical oxidation of organic matter (excluding the one required for nitrification). In a few words, the higher the COD/BOD_5 ratio is, the more difficult it is to biologically remove via biodegradation the pollution. For domestic wastewater, this ratio ranges between 2 and 2.5. A COD /BOD_5 ratio greater than 3 indicates pollution of industrial origin or the presence of toxic substances inhibiting biological activity.

Now that we understand the importance of treating the wastewater we produce, let's find out how traditional wastewater treatment plants work, the microorganisms responsible for the wastewater purification and how these systems help protect our health and the planet we share!

7. **'*Mummy what happens to poo when it is flushed away?*'** Every parent has encountered this question from their curious child, and the answer is more fascinating than one might expect. When you flush the toilet, your waste embarks on an incredible journey through a wastewater treatment plant, where microbes, our invisible friends, play a crucial role.

A wastewater treatment plant works like a giant washing machine that cleans dirty water. There are several processing phases in a conventional treatment plant in which wastewater is progressively cleaned before it goes back to a river, sea or ocean.

The first step is the **collection** of wastewaters from homes, offices, schools that travels through large pipes to the plant, like a road system but for water. When the wastewater arrives at the plant, larger objects like paper, plastics, metals are removed (**screening**) using filters to prevent damage and clogging of downstream treatment equipment. Next, the wastewater moves into large **settling** tanks where solids, sand and small stones settle to the bottom.



The liquid stream on top goes into tanks (aeration basin) where the **biological treatment** occurs. Here the activated sludge, mostly organized in small bacterial aggregates called "flocs", is maintained in suspension by the mixing action of air diffusers ensuring the bacteria are held in contact with the soluble organic matter in the liquid. The organic pollutants are thereby rapidly degraded in the presence of oxygen which is continuously replenished by the aeration system. In a few words, the microbes grow using the organic compounds and nutrients as sources of food and energy by breaking them down to carbon dioxide which is released as a gas from the treatment plant.

Other microorganisms, larger in size than bacteria and more complex, contribute to the purification of water. They include Protozoa, mostly Ciliates which eat the free-living bacteria (not aggregated in the biological flocs), enhancing the clarity of the final effluent.

The biomass – the mass of microbial cells present in the flocs – is finally separated from the liquid phase by gravity **clarification** in a separate tank which allows it to settle down. The clean water on top moves to the last step, the **disinfection** phase that can be performed using chlorine, ultraviolet light or ozone to kill most of the remaining microbes, in particular any pathogens that were not killed off in the activated sludge process, and to make the water safe to go back to nature.

A portion of the biomass enriched of precious microbes able to efficiently degrade the organic contamination of the wastewater is then recycled to the head of the plant to guarantee optimal wastewater treatment performances.

8. ***Why do we use bacteria for producing clean water from waste?*** The answer can be found in the unique peculiarities of our invisible friends:

- They **naturally occur** in raw sewage, rainwaters, soil leaching etc. We do not need to add any external specialized microorganisms to the treatment plant because the selection and the enrichment of specialized microbes is made by applying the proper operating conditions (e.g. oxygen concentration, adequate retention time of microorganisms in the oxidation tank etc.)
- They can remove a wide range of compounds because of their amazingly **wide metabolic versatility**: they eat almost everything efficiently and rapidly. This is due to their small size, just a few microns (1 micron is 0.001 mm), which gives them a high surface-to-volume ratio, allowing them to rely on growth material diffusing into the cell (and wastes diffusing out) to flourish. When surface area is greater than volume, substrates (e.g. contaminants, nutrients etc.) are transported more efficiently into, out of, and around the cell (**high nutrient transport rates**). The higher the surface area to volume ratio they have, the more effective the degradation of pollutants can be. Larger organisms require specialized organs such as lungs, kidneys, intestines, circulatory system etc. allowing to effectively increase the surface area available for exchange processes and to move material inside the body.
- Most of them **grow fast**. When enough food is available, bacteria can reproduce rapidly by growing and dividing into two identical cells. In a wastewater treatment plant, many bacteria can double in number every 20 to 30 minutes.

In summary, the basic function of wastewater treatment is to speed up the natural processes by which wastewater is normally purified in the environment, by using an engineered system working under controlled operating conditions and higher rates. When a small amount of wastewater is dumped into an aquatic ecosystem, a natural self-purification process begins thanks to the action of bacteria and other small organisms living in the water. They consume the organic matter and nutrients, turning it into new bacterial cells producing carbon dioxide and other products. However, the self-purification and resilience capacities of our aquatic ecosystems are limited and incapable of handling the huge volume of domestic and industrial wastewaters produced every day. It is therefore our duty to give nature a helping hand by properly treating the wastewater we produce. This we do in wastewater treatment plants. In what follows, we shall also see how each of us can help to keep a clean and healthy environment.

9. ***Recovery of nutrients.*** Microbes perform amazing work in water treatment plants. One of their ‘superpowers’ is the capacity to efficiently remove essential nutrients like nitrogen (N) and phosphorus (P) from the wastewater, preventing these nutrients from polluting our aquatic ecosystems. When in excess, N and P can cause eutrophication, the overgrowth (*bloom)* of photosynthetic organisms (e.g. algae, cyanobacteria) which causes water turbidity and harms water quality. These blooms limit light penetration, causing the death of aquatic plants. When the algal blooms eventually die, their decomposition by microbes severely depletes the oxygen of the water, creating zones lacking sufficient oxygenation to support the life of most organisms. The ingestion of eutrophic water may cause several health problems like skin irritation, gastroenteritis as well as rare but serious illnesses like methemoglobinemia.

Now that we have explained the damage high levels of N and P can cause in water ecosystems, let's discover how microbes remove these nutrients from wastewater, preventing eutrophication.

Nitrogen removal. Ammonia (NH_3) is the primary component of urine. It is consumed by highly specialized groups of bacteria, collectively known as *nitrifiers* or *nitrifying bacteria* which are able to oxidize it to an easily absorbable form of nitrogen, nitrate (NO_3^-). They are able to grow on inorganic nitrogen according to the following general reaction which provides energy for the bacteria engaged in this process:

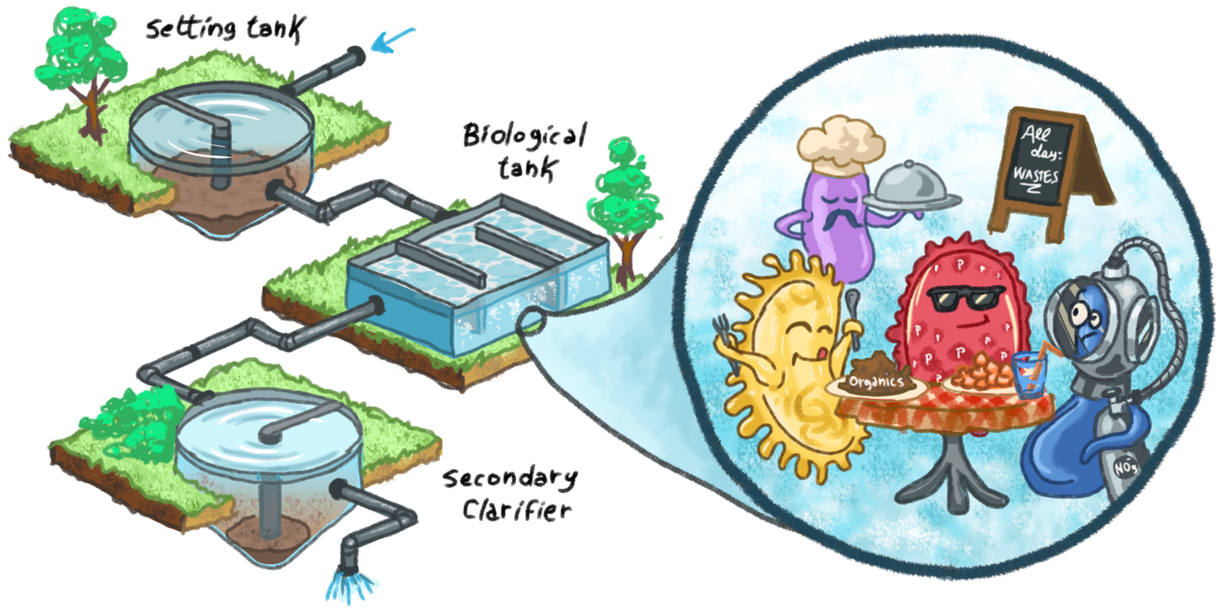
$$NH_3 + 2O_2 => NO_3^- + H_2O$$

A few microbes are currently recognized as nitrifiers. They include bacteria belonging to the well-known *Nitrosomonas* and *Nitrobacter* genera. *Nitrosomonas* transforms ammonia to nitrite (NO_2) whereas *Nitrobacter* turns nitrite into nitrate. Both can act only in the presence of oxygen, using inorganic CO_2 as a carbon source for their growth. They can easily be found as small, compact aggregates occurring on the surface of the activated sludge flocs.

Nitrate can be then fully removed in a separate, not-aerated tank (*anoxic basin*) by **denitrification**. This process is driven by bacteria known as *denitrifier*s, which grow on organic matter by respiring nitrate instead of oxygen. Nitrate is converted to nitrogen gas (N_2) which is released back into the atmosphere. In this way, nitrifiers and denitrifiers work together efficiently to produce clean water from wastewater and keep a healthy environment.

Phosphorus removal. Over the past decades, design advances have allowed treatment plants to remove not only organic materials and nitrogen but also phosphorus, thanks to the action of another amazing group of bacteria called Polyphosphate Accumulating Organisms (**PAOs**). These bacteria have the remarkable ability to remove more phosphorus than they need for normal metabolic requirements by storing it as polyphosphate granules inside their cells. The biomass separated from the liquid stream in the settling tank is therefore enriched in phosphorus and the overall water quality produced by the treatment plant is optimal as a result of the carbon and nutrients efficiently removed.

The process, called **Enhanced Biological Phosphorus Removal (EBPR)**, is carried out in an anaerobic basin (without oxygen and nitrate) receiving wastewater where carbon is accumulated as storage material inside the bacterial cells and phosphorus is released as soluble phosphate. In the subsequent aerobic basin, the stored carbon material is degraded and used for bacterial growth while most of the released soluble phosphate is taken up by the sludge microbes and stored as polyphosphate granules. One of the most well-studied PAOs is *Accumulibacter*. Under a microscope, PAOs appear as nice clusters of cells inside the activated sludge flocs. The polyphosphate granules stored in these useful microbes can be easily visualized by using a specific stain coloring them a lilac color.



10. ***Production of the waste sludge: energy production and even more.*** When wastewater from toilets, sinks, and drains is treated at wastewater plants, a by-product called waste sludge is produced. While often seen as waste, sludge is a valuable resource with great potential. Let's find out why it is more than just waste by answering some questions together!

What is Waste Sludge? Waste sludge is a thick, muddy substance composed of solid particles removed from wastewater. Rich in organic matter, nutrients, and microorganisms, sludge has significant potential as a resource but must be managed carefully to avoid environmental issues.

How is Waste Sludge Produced? Waste sludge is generated through key steps in the wastewater treatment process:

- **Settling**: Wastewater passes through screens and settling tanks to remove large debris. Heavier particles settle at the bottom, forming primary sludge.
- **Biological Treatment**: The remaining water moves into tanks where microorganisms break down organic pollutants, creating secondary sludge.
- **Clarification/Sludge digestion**: The combined primary and secondary sludge is thickened, stabilized, and processed to reduce its volume and make it safer to manage.

Why Does Waste Sludge Matter? Though often overlooked, waste sludge is rich in organic matter and nutrients, making it a valuable resource for energy production and other beneficial uses. By transforming waste sludge, we can develop innovative solutions for energy and sustainable resource management.

One impactful use of waste sludge is **biogas production**, a sustainable process that reduces waste while generating renewable energy. Biogas production relies on **anaerobic digestion**, a process in which waste sludge is broken down by naturally occurring bacteria in an oxygen-free environment through three stages: hydrolysis – the breakdown of complex materials like polymers into their simple components (e.g. monomers), acidogenesis/acetogenesis – the breakdown of monomers to cellular metabolites, and methanogenesis, producing methane-rich biogas.

This biogas is a versatile energy source that reduces reliance on fossil fuels and supports energy self-sufficiency. It can be used to generate electricity, provide heat, or be upgraded to biomethane.

Co-digestion, which involves mixing sludge with other organic materials, boosts biogas production and promotes sustainable waste management by diverting organic waste from landfills. It also produces digestate, a high-quality fertilizer, and contributes to a circular economy by turning waste into valuable resources.

Beyond energy, waste sludge can be used to create biopolymers, biodegradable alternatives to traditional plastics (**bioplastics**) with diverse applications, from packaging to medical devices, helping to reduce plastic pollution. Waste sludge is also a source of other valuable compounds, including **biofuels, biodegradable lubricants,** and ingredients for **cosmetics.**

In summary, efficient management of sludge can transform it into valuable resources, supporting sustainability and environmental protection. Waste sludge is a crucial resource in the move towards a cleaner, greener future, offering solutions for energy production, waste reduction, and the creation of sustainable products.

11. ***Clean water for our ecosystems and human needs.*** Continually improving wastewater management creates opportunities for both pollution reduction and the augmentation of clean water supplies. Indeed, once we understand how a wastewater treatment plant works and the role of our amazing microbes, we can turn our attention to the clean water it produces. What happens to the water after the wastewater treatment? It usually goes to rivers or to the sea. However, in the latter case, this invaluable source is lost because it becomes seawater. After so much effort to produce clean freshwater from waste, we end up discharging it into the sea and we must desalinate it to get back freshwater again!

Did you know that freshwater makes up only 2,5% of the Earth's water, and most of this small amount is inaccessible because it is frozen in glaciers or stored underground? For this reason, freshwater is extremely precious, and we must be careful not to waste it.

Here's another cool part of the wastewater treatment plant: after treatment, the water can be used again! **Reusing treated wastewater,** instead of discarding it, can serve many important purposes:

- **Irrigation**: Farmers can use treated wastewater to grow crops, which helps us save fresh water from wells or rivers. Treated wastewater can be also used for watering gardens of our cities.
- **Helping nature**: Treated wastewater can help refill rivers, lakes, and groundwater supplies, helping plants and animals that rely on these water sources.
- **Recharging aquifers**: Aquifers are underground lakes of water that many people use for drinking. Recharging them with clean, treated water keeps these supplies abundant.

By reusing treated wastewater, we can help to protect the freshwater, especially during **drought** periods: every drop of water is precious, and it is up to all of us to take care of it. And we are not actually talking about just a few drops. The estimated global wastewater production is more than 350 billion cubic meters per year; this volume is significantly larger than most artificial lakes or reservoirs. To get an idea of this, the amount of wastewater globally produced every year is 4.5 times the volume of New York City! Unfortunately, only 52% of global wastewater is treated, and the amount of wastewater reuse is estimated to be only 11 % of the total volume produced.

12. ***What can we all do to improve wastewater treatment and support the actions of our small superheroes?*** Most people do not think much about wastewater treatment. Sewage flows from your home into a sewer system where it's handled without much concern from most of us:

"*out of sight, out of mind*". However, our daily habits can help improve the overall process and support the microbes doing the hard work for us.

What **can we flush** down the toilet? Only pee, poo and toilet paper. Toilet paper is specifically designed to dissolve in water. Although other paper materials seem similar, they don't disintegrate in water like toilet paper does. Flushing these materials can obstruct water flow and cause costly clogs in sewer pipes. Just because something can be flushed down the toilet does not mean it should be. In the sewers you can find everything, even unthinkable things that can obstruct and damage treatment systems, inhibit the action of microbes with the effect of compromising the treated water quality and negatively impact on the receiving rivers, lakes and seas. Have you ever thrown something other than toilet paper into the toilet? It's better not do it again if we want these systems working properly and protecting the environment.

So, what **can't we flush down** our toilets?

We should never throw in the toilet items that should be treated as solid waste and thrown into the garbage since wastewater treatment plants are not designed to dispose of them. These items include:

- *fats, oils, and grease* such as cooking oils, frying oil, meat grease and any other substance that gel or solidify at room temperature.
- *medicines, chemicals, paint, cleaning products*. These can pollute rivers, streams, and oceans, and may even seep into aquifers, with harmful effects on public health. Use non-toxic household cleaners, to minimize chemicals in wastewater. Medicines must be disposed safely at pharmacies or at different locations having permanent drug disposal boxes.
- *paper towel and napkins, tissues and towels, make-up remover pads, wet wipes, pads and tampons, diapers.* Even though some of these products are indicated as biodegradable on the packaging, they may contain rayon, viscose or other chemicals. They are designed to absorb liquid and when flushed, take in a lot of water and expand leading to costly blockages.
- *cotton buds and cigarettes and chewing gum*. These items are not biodegradable and can enter water bodies, causing damage to treatment systems beforehand. Cotton buds contain plastic and can take as long as 500 years to biodegrade. Cigarettes contain harmful chemicals that can contaminate water supplies and harm aquatic life.
- *hair.* Both human and pet hair do not dissolve in the water and can severely block pipes preventing water from flowing through.

We also need to limit our use of garbage disposals, which dump organic matter into sewers and consume large amounts of water. Additionally, conserving water helps reduce the volume of wastewater we produce daily and improves the effectiveness and efficiency of wastewater treatment plants. We can do this by for instance the use of low-flow toilets and shower heads or washing only full loads in washing machines and dishwashers. As is often the case, everyone's contribution can help!

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 diseases, reduce the number of deaths and illnesses from hazardous chemicals and water pollution and contamination).*

Educating children about wastewater treatment helps them to understand the huge problem of human waste, the hazard for the health of humans and the biosphere it poses, the crucial need for effective reduction and the rendering safe of waste, and the vital role of wastewater treatment in supporting human health and sustaining all life. Microbes in wastewater treatment plants are essential to reducing diseases, ensuring access to clean water, and protecting ecosystems - all key factors in achieving SDG 3. However, a large portion of the global population still lacks access to effective wastewater treatment facilities. This gap poses a major challenge to achieving Goal 3 of the 2030 Agenda, as untreated wastewater remains a significant source of health risks and environmental contamination. The impact is especially severe in low-income regions, where limited infrastructure and resources exacerbate waterborne diseases and pollution. Increasing investment in wastewater treatment infrastructure worldwide is vital to bridging this gap and ensuring health and environmental protection for all.

- **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*).

When we discuss the role of microbes in treating the wastewater we produce daily, we address a critical issue for the planet. Wastewater treatment is essential to providing sufficient clean water and proper sanitation for everyone. By treating wastewater, we make the water safe to be recycled and used again, ensuring there is enough water for drinking, cooking, and washing.

When treated effluent is diluted into another receiving waterbody, it helps replenish clean water supplies without causing the serious and often irreversible ecological damage associated with untreated discharges. Such untreated wastewater disrupts natural ecosystems and compromises the water's natural self-purification processes.

It has been recently estimated that at least two billion people globally still rely on unsafe drinking water sources contaminated with fecal matter, which leads to diseases like diarrhea, typhoid, cholera that remain leading causes of mortality worldwide. Unfortunately, recent data indicate slow progress toward the 2030 target of halving the global proportion of untreated wastewater discharges. Meeting this target requires stronger efforts to expand wastewater treatment infrastructure, especially in areas where untreated wastewater poses a major public health risk.

- **Goal 13. Take urgent action to combat climate change and its impacts** (*Reduce greenhouse gas emissions, mitigate consequences of global warming, strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries).*

Wastewater treatment plays a critical role in both maintaining water quality and mitigating climate change, making it highly relevant to SDG 13. Wastewater treatment plants help reduce greenhouse gas emissions by capturing and using biogas produced during treatment, as well as by optimizing nutrient removal to prevent nitrous oxide emissions. These facilities also support climate adaptation efforts by conserving water resources, especially promoting treated water reuse, resource recovery from effluents and aquatic ecosystems protection.

As climate change accelerates, investing in energy-efficient, resource-recycling, and climate-resilient wastewater treatment technologies will be essential to reducing the environmental impacts and ensuring sustainable development. This approach not only aids in climate mitigation but also ensures that communities are better prepared to face the challenges of a warming planet.

- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** *(Reduce marine pollution, protect and restore ecosystems).*

Biological wastewater treatment is essential to achieving SDG 14, as untreated or inadequately treated wastewater can severely impact marine ecosystems. Key pollutants from untreated wastewater include:

  - Nutrients that contribute to algal blooms and development of oxygen minimum zones, which disrupt marine life;
  - toxic chemicals and heavy metals that harm marine organisms and accumulate through the food chain, affecting ecosystems and human health;
  - microplastics and pharmaceuticals that endanger marine biodiversity.

Potential Implications for Decisions

- ***Individual***

a. Which is the best behavior I can adopt to help the wastewater treatment plant to work properly? To help wastewater treatment plants work more efficiently, there are simple behaviors you can adopt in your daily life. First, be mindful of what you flush or pour down the drain. Avoid flushing non-degradable items like wipes, cotton swabs, or sanitary products, as these can clog pipes and overburden treatment systems. Also, limit the amount of fats, oils, and grease you pour down the sink, as they can harden and block pipes, making it more challenging for the plant to treat wastewater effectively.

b. What can I do daily to reduce water consumption and pollution? In your daily routine, you can reduce water consumption and pollution by taking shorter showers, turning off the tap while brushing your teeth, and choosing eco-friendly cleaning products. Repair leaks in your home to avoid wasting water. Additionally, reduce the use of harsh chemicals like bleach or strong detergents, which complicate the treatment process and can harm the environment. By cutting back on water waste and pollutants, you contribute to a more sustainable and efficient wastewater treatment process.

2. *Community policies*

a. What rules can our community put in place to reduce the harmful substances which flow away through sewers towards a treatment plant? To help reduce the harmful substances entering wastewater treatment plants, our community can establish clear regulations and guidelines for both local businesses and residents. Businesses, especially those in sectors like restaurants, car washing, or industries that handle chemicals, should be required to install proper filtration systems to capture fats, oils, grease, and other pollutants before they enter the sewer system. For residents, a community-wide initiative could encourage responsible disposal of household items like cleaning products, medications, and non-degradable waste.

b. How can we encourage the use of environmentally friendly technology and infrastructure to improve wastewater treatment in our community? This can be achieved by offering incentives, such as tax breaks or rebates, to businesses and homeowners who adopt green technologies. Systems like rainwater harvesting, greywater recycling, and eco-friendly plumbing fixtures can help reduce strain on wastewater systems while conserving water.

c. What programs can we create to educate people about the importance of good wastewater management and its impact on our environment and health? A comprehensive educational strategy involving schools, local media, and community events can help raise awareness. Workshops or other meeting events can demonstrate how daily actions impact water quality, while partnerships with local businesses can promote green practices. Sharing information through social media or local newsletters can build awareness about wastewater management, helping people understand these technologies and their positive impact on the environment.

3. *National policies*

a. How may biological wastewater treatment support global efforts to fight climate change and protect the environment? National policies can prioritize wastewater treatment as a key element in climate change mitigation and environmental protection by integrating it into broader sustainability, energy, and climate strategies. Compliance with stringent regulations and adoption of sustainable wastewater treatment processes provide great opportunities for innovative solutions, enabling water reuse, recovery of renewable energy and nutrients. Implementing national standards for pollutant and nutrient in discharged wastewater, along with greenhouse gas emission targets for the wastewater sector, can protect water bodies and ecosystems and guarantee a safe reuse. Tighter discharge limits on effluents released into rivers, lakes, and oceans will ensure that wastewater treatment plants operate with minimal environmental impact.

Reducing the environmental impact of wastewater treatment would benefit from incentivizing emissions reductions. This can be achieved by promoting low-carbon, energy-efficient technologies and supporting carbon credit systems. Together, these measures make 'green' technologies more economically viable for companies, simultaneously limiting carbon emissions.

Moreover, setting comprehensive standards and guidelines for treated wastewater reuse, alongside mandates requiring industries to recycle a certain percentage of their wastewater, can substantially reduce freshwater demand. This fosters water conservation and encourages active participation from the private sector in national conservation initiatives.

While best practices are being implemented globally, adoption varies due to local policies, technology availability, funding, and public awareness. Consistent efforts are essential to standardize and promote these practices, enhancing the sustainability of wastewater treatment and its contributions to climate change mitigation and environmental protection. Targeted initiatives to address implementation disparities can facilitate a more uniform transition to sustainable wastewater management practices, thereby improving environmental resilience and resource recovery.

Pupil participation

1. Class discussion

a. Why is wastewater treatment vital to humanity?

b. What do you really know about wastewater treatment?

c. How does the wastewater treatment plant work?

d. Why are microbes important in cleaning wastewater?

e. How do microbes clean the wastewater?

f. Do you know what we shouldn't throw down the drains and why?

2. Pupil stakeholder awareness

a. Why do we need to clean water before it enters rivers and lakes? Can you think of ways we use clean water every day?

b. How do you think cleaning wastewater helps organisms in nature?

c. Do you think it is important for us to learn about how water is cleaned and the microbes that help? Do you think it is important to tell our friends and family about the importance of clean water and the role of microbes?

3. Exercises

a. Story Writing: Write an adventure story about a group of microbes in a wastewater treatment plant. What adventures will it have? How will our heroes clean the water? (e.g.: ‘Once upon a time, in a water treatment plant, there were tiny heroes called Mr. Nitrobacter, Ms. Nitrosomonas....’).

b. Drawing Activity: Draw a picture or create a poster about wastewater treatment plants. Include drawings of microbes, the stages of water treatment, and why clean water is important for health.

c. Digital Presentation: Create a simple digital presentation using PowerPoint about wastewater treatment plants. Include pictures of microbes, the stages of water treatment and what you have learned about microbes.

d. Vocabulary Match: Match the words (i, ii, iii) with their correct definitions (iv, v, vi)

i. Microbes
ii. Wastewater
iii. Wastewater Treatment Plant

iv. A place where dirty water is cleaned
v. Water that needs to be cleaned
vi. Tiny living organisms, some of which live in water and help to clean it

The Evidence Base, Further Reading and Teaching Aids

History of wastewater disposal and treatment through the ages:
Article: Lofrano, G., & Brown, J. (2010). Wastewater Management through the Ages: A history of Mankind. Science of The Total Environment, 408 (22), 5254-5264.
Educational video: https://www.youtube.com/watch?v=oBMVXXXTne0

Wastewater and nutrient management:
Educational video: https://www.youtube.com/watch?v=R0XQ5q7CsR8
Educational video: https://www.youtube.com/watch?v=itCOY7VviRU&t=38s
Educational video: https://www.youtube.com/watch?v=YW6GBciRHLg

Eutrophication:
Educational video: https://www.youtube.com/watch?v=92TFJTtuq6k
Educational video: https://www.youtube.com/watch?v=c9FcUegliMk

Clean water for our ecosystems and human needs
Article: Jones, E. R., van Vliet, M.TH., Qadir, M., Bierkens, M.F.P. (2020). Country-level and gridded wastewater production, collection, treatment and re-use. PANGAEA, https://doi.org/10.1594/PANGAEA.918731
Educational video: https://www.youtube.com/watch?v=j2xmvDZZqSo
Educational video: https://www.youtube.com/watch?v=GcQ_A_U00E8

Glossary

Aerobic respiration: production of energy coupled to the reduction of oxygen to water.
Anaerobic digestion: a biological process carried out by microorganisms able to decompose organic matter and produce biogas in the absence of oxygen.
Binary fission: process of bacterial cell division resulting in production of two similarly sized and shaped bacteria from a single parent cell.
Biochemical Oxygen Demand (BOD_5): analytical test indicating the degree of water pollution with biodegradable organic matter and measures the oxygen consumed by microorganisms during aerobic respiration.
Biogas: a gaseous mixture of methane and carbon dioxide produced during the anaerobic digestion process.
Chemical Oxygen Demand (COD): it measures the oxygen consumption resulting from the chemical oxidation of organic matter, both biodegradable and recalcitrant, to carbon dioxide.
Eutrophication: process leading to the overgrowth of algae into water bodies, eventually resulting in oxygen depletion and aquatic ecosystems failure and death. Eutrophication is caused by the discharge of wastewater containing high levels of nutrients such as nitrogen and phosphorus.
Fertilizers: a material used in agriculture to provide nutrients for plant growth.
Filamentous bacteria: bacteria growing in long strands in which cells do not separate from each other after cell division and appear in the form of filaments. They are beneficial in floc formation and contribute to the wastewater purification processes. However, under certain conditions, their overgrowth may interfere with the proper sludge settling causing the poor quality of the final effluent.
Methane: main component of biogas produced by specialized microorganisms in the absence of oxygen. It can be burned to produce energy and heat or used as transportation fuel.

Nutrients: all the substances providing essential nourishment for the growth, maintenance, and functioning of an organism.
Protozoa: unicellular eukaryotic microorganisms commonly inhabit the activated sludge and play an important role in wastewater purification processes.
Resource recovery: a series of processes and practices aimed at recovering valuable materials from wastes and making them available for the manufacturing of new products.
Waste sludge: the excess quantity of microorganisms that must be removed from the wastewater treatment plant to keep the biological system in balance.