Recovery of Resources from Wastewater

Daddy: Our teacher told us this morning that we should not waste wastewater anymore but use our microbial friends to recover valuable resources

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Willy Verstraete[a] and Silvio Matassa[b]

[a] Center for Microbial Ecology and Technology, University of Gent, Belgium
[b] Department of Civil, Architectural and Environmental Engineering, University of Napoli Federico II, Italy

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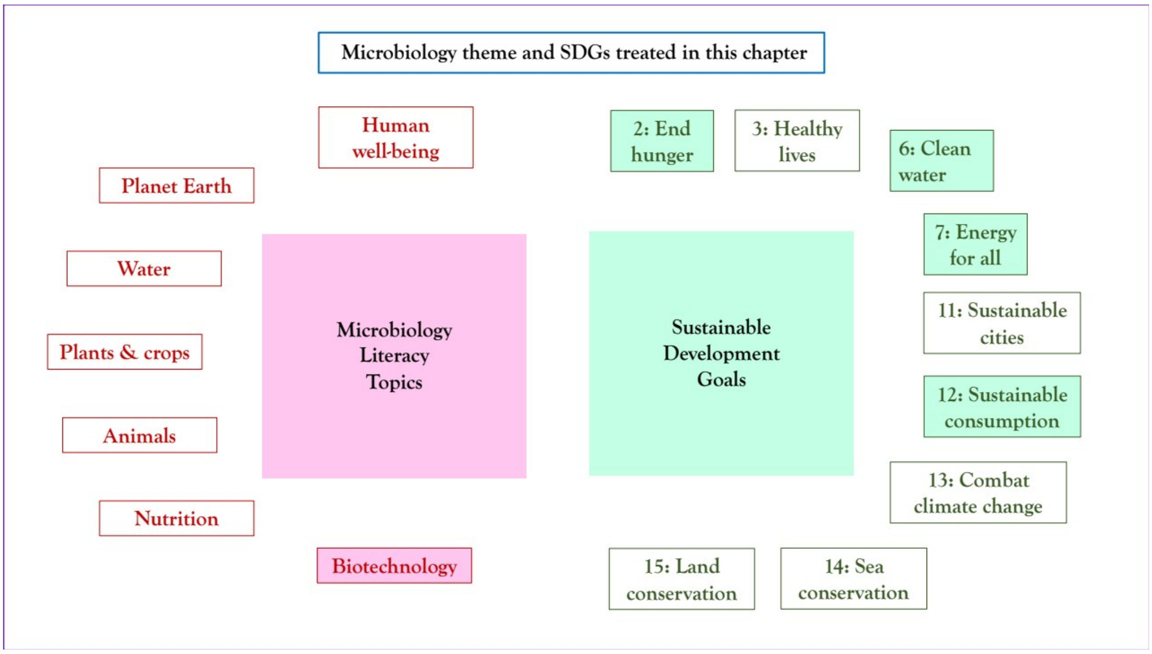
Storyline

Farmers produce for us food by cultivating plants and animals on the farm. Plants obtain energy for growth from the sun, and water from the soil. All cells – ours and those of plants – need large amounts of nitrogen for the production of proteins, and phosphorus for the production of genetic information materials and cell membranes. Because soil contains very little nitrogen in a chemical form plants can use, nor phosphorus, farmers add these as fertilisers, in order to boost crop yields. We eat the food farmers produce, and in our gut, our partner microbes also feed on this. Yet, we do not use all these nutrients and, when we go to the toilet, release what we do not use, plus all the microbes that have also been feeding on our food, into the domestic wastewater. Domestic wastewater (sewage) contains significant amounts of organic matter (unused food , microbes grown in out gut, gut wall components which are replaced by new ones, and so on), organic nitrogen and phosphorus. Organic matter is high in energy and can be converted by special microbes under the conditions set in the so-called anaerobic digesters, to a usable form of energy, namely methane, which is a form of natural gas. Microbes present in sewage convert organic nitrogen in wastewater to ammonium. Thus, the nitrogen coming from the farm in the form of food is set free and can be captured and recovered as a valuable resource (ammonium fertilizer) for us to re-use on the farm. Microbes can also recover phosphorus from wastewater. Finally, the water matrix of the sewage is also a valuable resource and, once organic matter, nitrogen and phosphorus have been removed from it, we can purify it further, for instance by filtration over a membrane, and re-use it. Recycling wastewater, recovering resources from it, and obtaining clean water, are all aspects of sustainable development.

The Microbiology and Societal Context

The microbiology: microbially-driven carbon, nitrogen and phosphorus cycle biotechnology; recycling; resource recovery; conversion of organic waste to biogas; biotechnology. *Sustainability issues:* production and consumption patterns; food and agriculture; water and sanitation; energy.



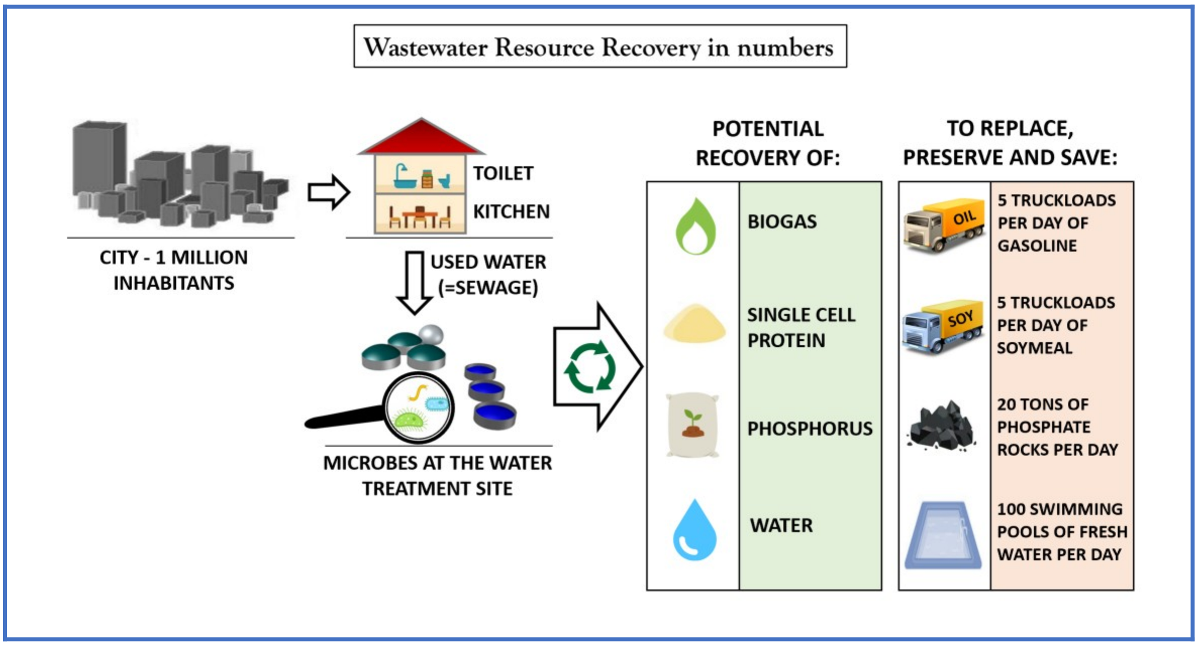
Recovery of Resources from Wastewater: the Microbiology

1. ***Wastewater is a valuable resource.*** Water enters our home in a pipe as clean water, which we use for various purposes: drinking, washing ourselves/clothes/dishes, flushing the toilet, and so on, and leaves in another as wastewater. This pipe leads into a collecting channel, part of a larger system called a sewer. The sewer brings the dirty water to the sewage treatment plant. The sewer may also collect rainwater from roofs and roads, as well as wastewater from industrial, commercial and agricultural enterprises. Typically, for a city of 1 million people, the volume of wastewater produced every day is 250 000 m^3 (some 250 L per person per day) which carries compounds and materials amounting to 150-200 tons dry matter per day (150-200 g per person per day). Traditional wastewater treatment plants use microbes to degrade and destroy as much of this material as possible. But now, we view sewage it as a source of valuable materials, to be recovered and recycled, and we use specific sets of microbes to achieve this. The major component of wastewater is organic material originating from feces, food waste, etc., which is energy-rich, and can be converted to biogas, from which the energy can be recovered. Other valuable materials in wastewater include nitrogen present in proteins, phosphorus in the genetic material of all cells and in some fats, and the water itself, which is becoming increasingly scarce in many parts of the world.

2. ***Organic matter can be converted to biogas.*** Microbes are great team players, and when provided with organic matter in anaerobic environments (that is: environments that lack oxygen), they organize themselves in a special way to break down complex organic molecules into simpler ones. This broad mix of molecules is used by a specific type of microbe, the methanogens, to produce biogas, composed of only 2 molecules – methane and carbon dioxide. Biogas is a useful source of renewable energy, that can replace non-renewable fossil fuel to provide electricity and home heating, or even to fuel our cars. To imagine how much biogas we could produce from the organic matter discharged every day in wastewater, we can make the following calculation. Say for example we consume every day 1.0 kg of organic matter (dry matter, compare it with sugar) and only use about 70% of this for our direct requirements. The remainder represents then 0,3 kg of organics, which is equivalent to about 0,1 L of fossil fuel. For a city of 1 million inhabitants, this represents about 100 m^3 of fossil fuel equivalents,

or 5 truckloads of gasoline, per day which, by modern fermentation technology, can be recovered and reused.

3. ***Organic nitrogen can be converted to ammonia.*** All organisms need large amounts of nitrogen for the production of proteins, such as enzymes that carry out the chemical reactions of the cell (its metabolism), regulatory proteins that control metabolism, structural proteins that move things around inside the cell and provide its scaffolding, etc. Although nitrogen gas is the most abundant element of the Earth's atmosphere, most plants cannot use it (the exception are those plants having nitrogen-fixing symbionts in their root systems), and require more reactive forms, like ammonia, nitrate and organic nitrogenous compounds – fertilizers – for growth. The industrial transformation of nitrogen gas to fertilizer involves very high energy inputs, ultimately provided by fossil fuel consumption. Thus, nitrogenous compounds are energy-rich and valuable resources to be recovered and reused wherever possible. However, once discharged into wastewater, used organic nitrogen is processed by treatment plants via a series of energy-intensive processes to nitrogen gas that returns to the atmosphere. We each consume about 100 g of protein per day, and excrete some 14 g of nitrogen. For the city of 1m inhabitants mentioned above, this represents another 30 m^3 of fossil fuel equivalent per day. Technologies currently being developed will allow the recovery and reuse of organic nitrogen in wastewater, so we will in the near future no longer destroy this nitrogen in the used water, but use microbes to set it free in the form of ammonium and then strip it out and upgrade it to produce new feed and food. In this case we could use specific microbes that are able to use renewable energy sources (for example hydrogen, methane, etc.) to directly convert the recovered nitrogen into protein-rich feed and food. We could even do this at the water treatment site and thus produce the equivalent of 5 truckloads of soymeal per day.



4. ***Phosphorus can also be recovered.*** All cells need phosphorus for the production of genetic information materials – the nucleic acids, cell membranes, the universal chemical currency of energy – ATP, and cellular signaling and regulatory molecules. Soil contains little phosphorus and, what is there is mostly present as complexes or absorbed on soil minerals, and thus insoluble and not available to plants. Although many root-associated microbes solubilize

phosphorus in their immediate neighborhood, this is still insufficient for maximal growth of crop plants. Therefore, farmers add soluble phosphorus fertilizer to boost crop yields. However, the production of fertilizer is energy intensive: for example, 1 ton of phosphorous fertilizer produced from phosphate-rich rocks in North Africa, requires the mining of some 20 tons of phosphate rock. And, more importantly, global phosphorous reserves are limited and current practices are predicted to exhaust these rocks within half a century. Hence, we need to conserve phosphorus stocks, and recover and reuse, as much as possible. Since some of the phosphorus added by the farmer as fertilizer is taken up by plants which we eat and is then release into the wastewater, there is an opportunity to recover at least some of the phosphorus in circulation. Certain microbes under specific conditions are able to accumulate phosphorus within their cells, and subsequently release it in a concentrated form that allows its recovery at the water treatment site. In practical terms, the wastewater produced each day by a city of one million people contains about 1 ton of phosphorus which can now be recovered by microbial technological processes.

5. Recovery of clean water. Most importantly, wastewater is about 99% water, also a very important resource that is scarce in many parts of the world. After harvesting the energy, the nitrogen and the phosphorous in wastewater, with the help of our microbial friends in the treatment plant, we can recover clean fresh water, ready to re-use for our daily needs, by filtering the residual water through membranes or sand beds. For a city of 1 million inhabitants, this represents a volume of 250 000 m^3 water every day. If we recover and re-use it, we do not have to get this amount from the precious and commonly overexploited natural reserves, like groundwater and surface waters.
Clearly, used water is a great resource and microbes are crucial to make it part of the cyclic economy.

Relevance for Sustainable Development Goals (SDGs) and Grand Challenges

Resource recovery from domestic wastewater relates to several SDGs (*microbial aspects in italics*), including

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture** (*end hunger and malnutrition, increase agricultural productivity)*. The production of nitrogen fertilizer is energy-intensive, it actually represents some 2-3% of all energy used in the world. Microbial recovery of nitrogen from wastewater in a form that can be used as a fertilizer, or even directly as feed or food, decreases energy consumption, and offers a solution to the problem of decreasing agricultural productivity. Phosphorus reserves are limited and are estimated to last only for the next 50 years. So microbial recovery of phosphorus from wastewater extends the lifetime of available stocks, without reducing agricultural productivity.
- **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)*. Water is a precious commodity that is used in vast quantities for all manner of domestic and industrial activities. Water reserves, in the form of groundwater, and surface supplies, in the form of rivers, lakes and reservoirs, are becoming depleted and competition for

them is already, or is becoming, a reason for regional conflicts , as for instance in the Middle East countries. The recovery of clean water from wastewater is thus of crucial importance in water management worldwide. The removal of organic matter, nitrogen and phosphorus by microbial processes are key elements in water recovery.

- **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)*. The growing world population demands growing energy supplies. Microbes convert energy-rich organic matter in wastewater to biogas, which is a renewable form of energy.
- **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)*. Though organic matter, nitrogen and phosphorus are valuable resources, if released into the environment as they have been in the past, they are polluting. In particular, nitrogen and phosphorus promote the growth of algae in surface water bodies, like lakes, rivers and coastal waters, which become eutrophic, and sometimes dangerous, if the algae that grow produce toxins. Resource recovery from wastewater thus prevents pollution by wastewater. Moreover, it contributes substantially to sustainable production, in this case of nitrogen compounds and phosphorus, of food crops, and their consumption.

Potential Implications for Decisions

1. ***Individual***

a. The volume of wastewater to be handled by the wastewater treatment plant grows with the number of dwellings it services. At a certain point, it reaches the limit of its capacity, and a new one must be created, involving significant expenditure of tax revenues, energy, materials and especially valuable land. Therefore, every effort to decrease the wastewater volume should be made by everyone. The amounts of freshwater used/wastewater released by a household – *its freshwater footprint, its wastewater footprint* – are highly variable, depending for example on how long we stand under the shower, how often we flush the toilet, how much water we use to wash up, etc. A typical value is about 100 L per person per day (10 buckets!). Note that this amount is in the sewer enlarged by various other water discharges. By restricting the way we use water (toilet use, showers, …) each of us can influence the amount of water to be treated.

b. Traditionally, different wastes have been combined and disposed of as highly complex mixtures, which are difficult to treat. Separation at source and concentration (amount of recoverable resource per unit of waste) is crucial to proper recycling. As more and more special microbial processes are employed to recover resources from wastewater, it becomes important to avoid disposing of non-essential materials, especially toxic materials that can perturb microbial processes. Also, the excessive use of freshwater will dilute wastewater, and will make it more difficult and costly to recover resources from it. So, we need again to reflect on the use of fresh water as well as on the disposal of strong cleaning agents, pesticides, and so forth.

c. Wastewater distribution networks and treatment plants can also be perturbed by solid materials, such as cleansing wipes, dental floss, etc., disposed of in wastewater, so we should consider alternative disposal routes.

d. Fats and grease tend to coalesce and solidify into larger masses, also affecting networks and treatment plants, so we need to consider alternative disposal and recycling options.

2. ***Community policies***

a. Institution of new resource recovery technologies require capital investment and expertise. Typically, the costs per person whose wastewater has to be sewered and treated amount to 600 Euro for sewer construction and 100 Euro for engineering and building of the treatment plant. The money that is used for these purposes cannot be used for building schools or sports fields.

b. Public education on household routines is necessary for good operation of wastewater treatment plants. To teach such facts and figures, a relevant policy decision is necessary, and this can be integrated into education/instructions on sustainable use of freshwater and discharge of wastewater.

c. Public awareness of the importance of resource recovery, and consumer acceptance of the recovered product, is essential to create the market opportunities needed to make resource recovery economically feasible. The inhabitants of a village or city must understand and learn to accept that the water they discharge does not "disappear" forever, but soon returns in the form of various recovery products. These 'facts of life' need to be learned through education and awareness-raising campaigns

3. ***National policies***

a. Fertilizer use, eutrophication and fertilizer pollution of groundwater reserves are a topic for national policy, so N and P recovery and reuse in a more efficient manner, and the associated updating of wastewater treatment plants, may fall under this remit

b. Similarly, ensuring adequate renewable energy supplies is national policy, so recovery of wastewater energy falls under this remit

c. Also, in some countries with scarce freshwater supplies, water provision is national policy and recovery from wastewater can be a key policy issue

Pupil Participation

1. Class discussion of the nature of wastewater and the recovery of its valuable resources: what do politicians need to do to increase resource recovery?

2. Pupil stakeholder awareness

a. How long do I stand in the shower? Can I decrease my freshwater/wastewater footprints?

b. What do I dispose of via the toilet/sink that should be disposed of in a different manner? What are the possible consequences?

3. Exercises (could be made at any level, but these are probably secondary education level)

a. How might we decrease the amounts of fertilizers used in farming?

b. Looking at the SDGs, how can we change our habits to improve the provision of food, water and energy?

The Evidence Base, Further Reading and Teaching Aids

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Glossary

Anaerobic digestion: A biological process carried out by microorganisms that, in absence of oxygen, are able to decompose organic matter and produce biogas;

Biogas: a gaseous mixture of methane and carbon dioxide produced during the anaerobic digestion process.

Carbon dioxide: a gaseous compound produced by the oxidation of organic carbon by means of biological or thermochemical processes. Carbon dioxide makes up almost 50% of biogas and, as greenhouse gas, contributes to global warming when it accumulates into the atmosphere;

Eutrophication: a cascade of processes leading to the overgrowth of algae into water bodies, eventually resulting into 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;

Greenhouse gas: gaseous compounds causing an increase of the natural greenhouse gas effect of earth's atmosphere and, hence, contributing to global warming;

Methane: composed by carbon and hydrogen, methane is the main component of biogas and holds a greenhouse gas potential 25 times higher than carbon dioxide. Methane is a precious energy vector and can be burned to produced energy and heat or used as transportation fuel;
Microbial protein: Biological, protein-rich material produced by microorganisms as part of their natural metabolism. Microbial protein can be used in animal and human nutrition, as organic fertilizer or even as building block for biodegradable polymers such as bioplastics;
Microbiome: a team of selected microorganisms that are able to cooperate and perform complex tasks together;
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;
Wastewater treatment plant: A facility designed to treat wastewater through a series of biological and physical-chemical processes. Pollutants such as organic substances and nutrients are removed to make wastewater dischargeable into natural water bodies;