Microbial polymers and bio-based plastics

Dad, why do you now wrap my sandwiches with paper? You were always using plastic.

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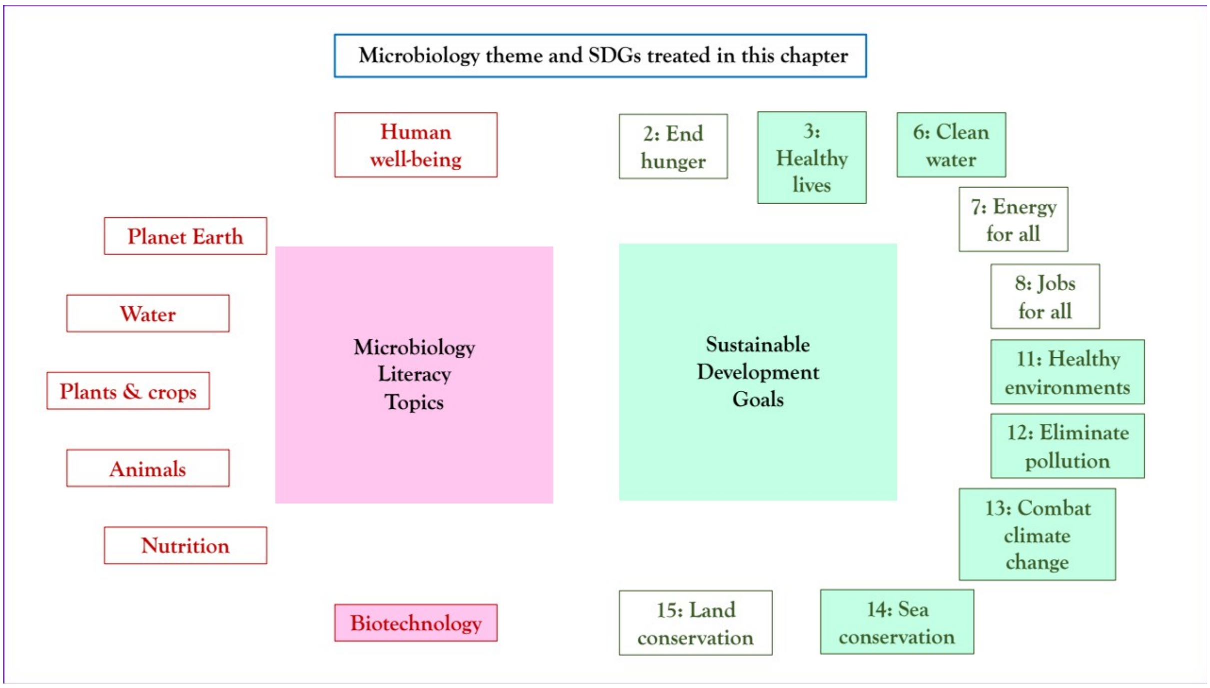
Storyline

Plastics have become an essential part of our lives. Their ductility and low cost offer countless benefits, such as the possibility to produce light but strong car components, high precision parts for hospital medical devices, and packaging that protects food against pathogens. Yet despite their many advantages, the mass production and use of plastics is causing serious damage to the environment, polluting the oceans and their wildlife, and ultimately harming people's health. This impact could be reduced by changing our system of production and consumption to make efficient use of available resources and develop new environment-friendly materials. Excessive use of plastics poses a threat to the environment and human health. Solutions to these challenges form an integral part of the United Nation's Sustainable Development Goals.

The Plastics and Societal Context

The plastics: landfill and Plastic Island in oceans; freshwater and soil pollution; toxic metal presence; cause of death of animals; microplastics accumulation in tissues and health problems; non-renewable sources; non-degradable sources; greenhouse gas emissions. *For completing the framework*: environmental and economic impact; lack of policies and societal actions.



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1. The packaging used to preserve sandwiches illustrates the extensive use of plastics in everyday life. Many objects used in homes on a daily basis, such as toys, combs and toothbrushes, are made of plastic. A look at a car will reveal that many of its parts are plastic, and single-use materials found in hospitals, including gloves and syringes, are also plastic. The same is true for food. Plastics are used as protection against bacteria, increasing the shelf life of products such as meat and fish. If we compare our grandparents' lives with our own, we notice that theirs were less sophisticated. Their toys were made of wood instead of plastic; they bought their food in marketplaces where it was sold unpackaged. And not everyone had a car. Today's consumerist lifestyle means that, by and large, people now have a great deal more things than in the past. Even clothes are different. Where our grandparents used wool and cotton, much of what we wear is made with synthetic, plastic-based materials. Plastic is so widespread because it is inexpensive, durable, waterproof and flexible, among other outstanding properties. Plastics have given us many benefits and made our lives easier, but their production and applications have increased exponentially over the past fifty years. In 2018, 360 million tonnes of plastic were produced worldwide, whereas in 1990, only 100 million tonnes were produced.

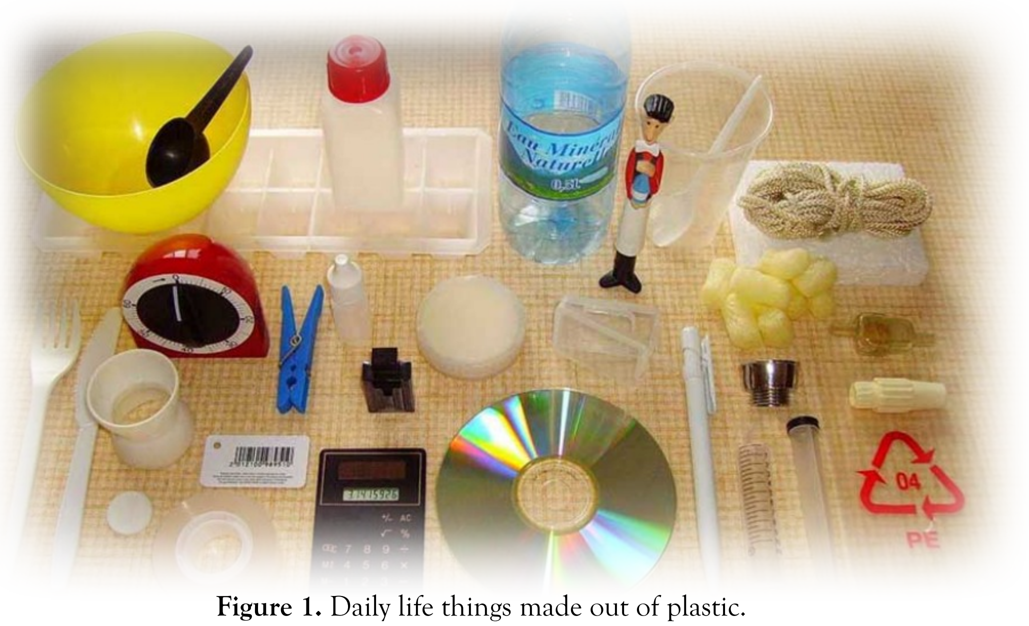

Figure 1. Daily life things made out of plastic.

2. For all their benefits, plastics have become a serious challenge to our health and our planet. Only one plastic bottle is recycled out of every ten thrown away. Many of those end up on our beaches and oceans, forming massive islands of plastic that drift afloat. Plastic's pervasiveness in the environment, which is mainly due to its remarkable **durability**, has already been proven to have a harmful impact on ecosystems. Petroleum-based plastics, such as those used in bottles and some clothes, are estimated to have a natural decomposition time lasting hundreds or even thousands of years. In this slow process of degradation, a piece of plastic or textile fibre is gradually fragmented by the mechanical action of water, wind and microbes, into smaller and smaller particles, ultimately forming **microplastics**. These plastics and microplastics end up being eaten by animals, often causing their death. Sometimes these microparticles **bioaccumulate** in the body tissues of these animals, which are later eaten by people, eventually leading to serious health problems[1]. In addition to microparticles, the degradation of plastics produces chemicals and toxic substances used as additives which are released into the soil and the seas, thus polluting these ecosystems. What actions are being taken to improve plastics management? Can plastic production be diminished?

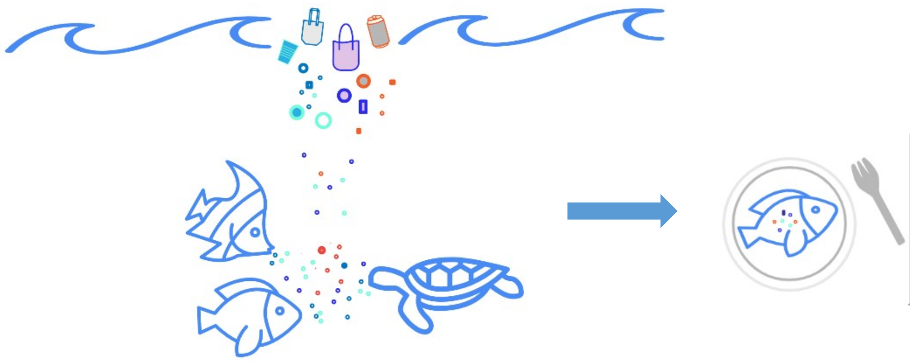

Figure 2. Microplastics pollution in oceans. Plastic debris is broken down into smaller particles, which are taken up by marine animals, and accumulated in their tissues. Ingestion of these animals will potentially affect human's health.

3. ***Our production system is linear: produce, use, throw away.*** This system leads to the generation of large quantities of accumulated waste, including plastics, and the depletion of our raw materials (oil, wood), which are by no means unlimited. The **circular economy** is a way to reduce waste and protect raw materials. This approach will transform our current linear productive system into a circular system, where waste management is based on the concept of the **3 Rs**: **reuse**, **reduce, recycle**. This concept revolves around three key actions: **reusing** objects that have been used before, which extends their useful life and will reduce the habit of relying on single-use products; **reducing** consumption by changing life habits, which diminishes the amount of generated waste; and **recycling** that waste by using it as a raw material for production, thus turning our existing linear system into a circular system.

Only 31% of the plastic produced in Europe is currently recycled, 27% is dumped in landfills, and 42% is burnt in incineration plants. So: for every 100 bottles thrown away in Europe, 27 are dumped in landfills, 42 are burnt, and only 31 are recycled. Recycling means processing waste to transform it into new materials, so that no fresh raw materials are needed. The 3 Rs approach can be expanded with a **further 3 Rs**:

- **Redesign:** innovative, creative ideas have the power to transform waste into opportunities and high-value-added products.
- **Repair:** we should be able to repair products that do not work instead of just throwing them away.
- **Recover:** collecting used materials rather than releasing them into the environment, so that they can be properly processed for recycling.

In this extended **6 Rs** concept that results from the combination of the above actions, each of the stages of the circular economy is strengthened.

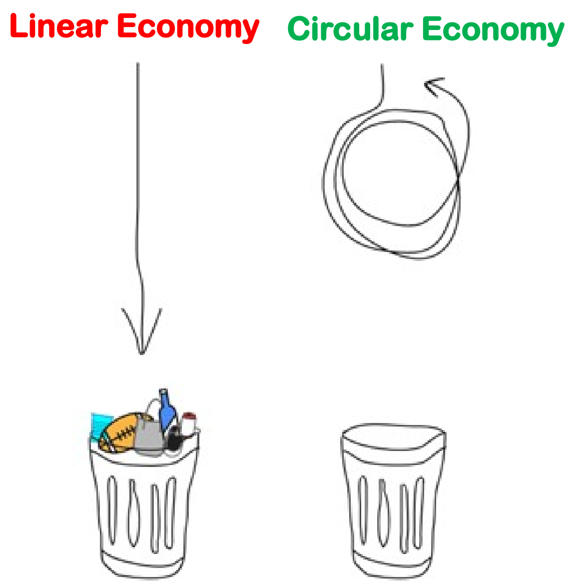

Figure 3. Comparison between the production chains of the linear economy and the circular economy.

A circular-economy system for the transformation and use of waste can reduce the amount of new waste released to the environment. **However, what about the plastic that is already in the oceans, on the beaches and in landfills?** Plastic takes a long time to decompose naturally. If we were able to collect it, its degradation could be accelerated by burning or using chemical processes or domesticating microorganisms to degrade it. **Incineration** of plastic waste is widely used in some countries, such as Switzerland, Austria and Finland. Burning recovers some of the energy present in plastics, which is harnessed to heat homes in the wintertime. However, in addition to energy, CO, CO_2 and metals that are harmful to the environment are also released into the atmosphere when plastics are burnt. To prevent an increase in greenhouse gases, these gases would need to be recovered and reused. A greener, less environmentally harmful option has been proposed in the field of biotechnology, which envisages using microorganisms to degrade plastic waste.

4. How can microbiologists and biotechnologists help reduce the impact plastics have on the environment? Bacteria are the most abundant organisms on the planet. They are found in all kinds of habitats: in fruit, soil, animals' digestive tracts, in the sea depths, hot water springs, ice, and even in radioactive waste. Their evolutionary success is partly due to a versatile and robust metabolism. Some bacteria are able to obtain the carbon they need from CO_2, while others find it in organic matter. Light is the source of energy for some, and others derive it by oxidising a chemical compound or a gas, such as hydrogen.

Microbiologists study the diversity of microorganisms, their behaviour, growth, metabolism, and how they can be utilised in industrial processes, turning them into "microfactories" for production. Many food products, such as bread, cheese and beer, have been made this way for thousands of years, before the existence of microorganisms was known. It was the French microbiologist Louis Pasteur who discovered that microorganisms were responsible for the fermentation processes that take place during the production of these food products. Today, processes in which microorganisms have a role in making products that are beneficial to humans are studied and developed in **microbial biotechnology**. Biotechnologists deploy their expertise to derive valuable compounds such as vaccines, insulin and antibiotics from microorganisms using genetic and biochemical means. Thanks to the versatility of microorganisms, biotechnology is used in the food industry and in medicine. More recently, it has started to be applied in the treatment of wastewater, toxic waste, and even urban refuse.

Essentially, there are two ways that microbial biotechnology can contribute to overcome the impact of plastics in the environment. One might be by decomposing the oil-based plastics, by contributing to recycle and/or reducing their persistence in the open environment. The second option is to generate new environmentally-friendly materials, suitable for use in some of the most contaminating applications of conventional plastics, such as food packaging.

5. If we took a piece of drifting plastic from the ocean and observed it through a microscope, we would see millions of bacteria living on its surface. Plastic fragments released into the oceans over hundreds of years are colonised by microscopic organisms, forming microbial communities that include bacteria, yeasts and diatoms. This plastic and microplastic debris has become a new ecosystem within our oceans, called the ***plastisphere*** (Fig 4). Microbial communities colonise the plastisphere, using their metabolic versatility to adapt. Some bacteria are able to obtain micronutrients, such as iron and cobalt, as well as energy, from metals found on the surface of plastic fragments. Certain bacteria have **enzymes** capable of altering plastics, including polyethylene terephthalate (PET), which is the material most water bottles are made of. PET is a tough, difficult to degrade polymer. Bacteria grow around microplastics forming **biofilms**, and secrete **extracellular enzymes** through their cell wall into the environment.

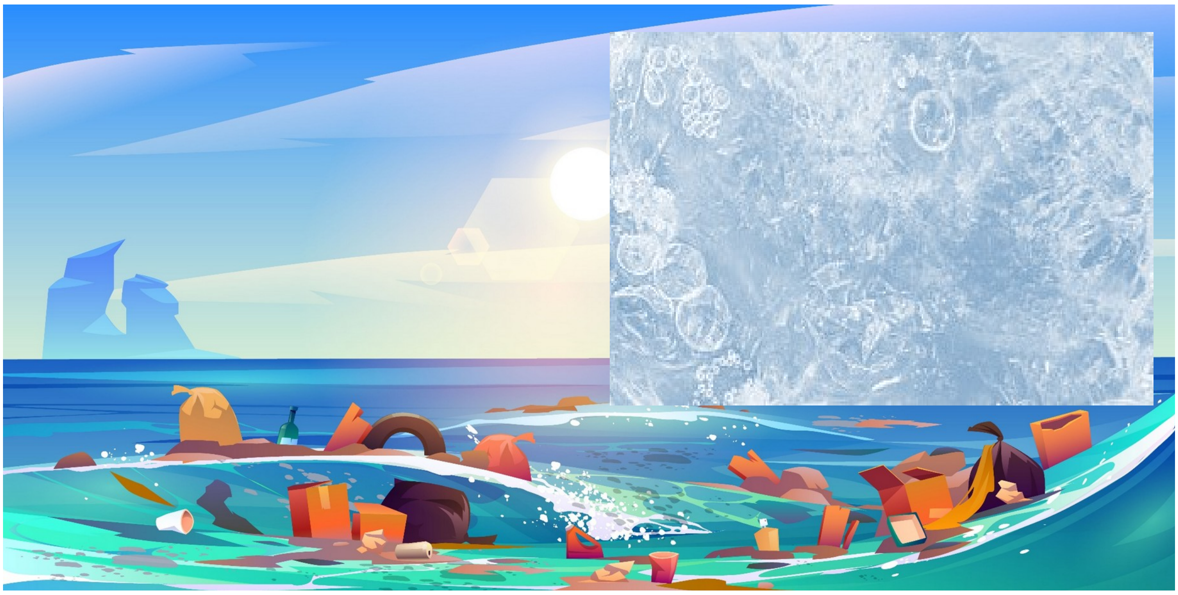

Figure 4. Cartoon mimicking a microbial community forming biofilms on the surface of the marine plastic litter as a miniature ecosystem that includes many types of microorganisms. Extracellular enzymes secreted by the member of communities are represented in purple and yellow colours[2].

A very simplified view of this strategy can consider that these extracellular enzymes might act very much like scissors, as if they were taking apart a Lego toy (i.e. the plastic polymer) into its elementary constituents (i.e. the monomers). They use the simplest Lego parts (i.e. monomers), to build new toys (i.e. bacterial structures or new upgraded bioproducts) (Fig. 5). The problem is that these enzymes are naturally not efficient in the open environment and do not significantly contribute to plastic degradation in Nature.

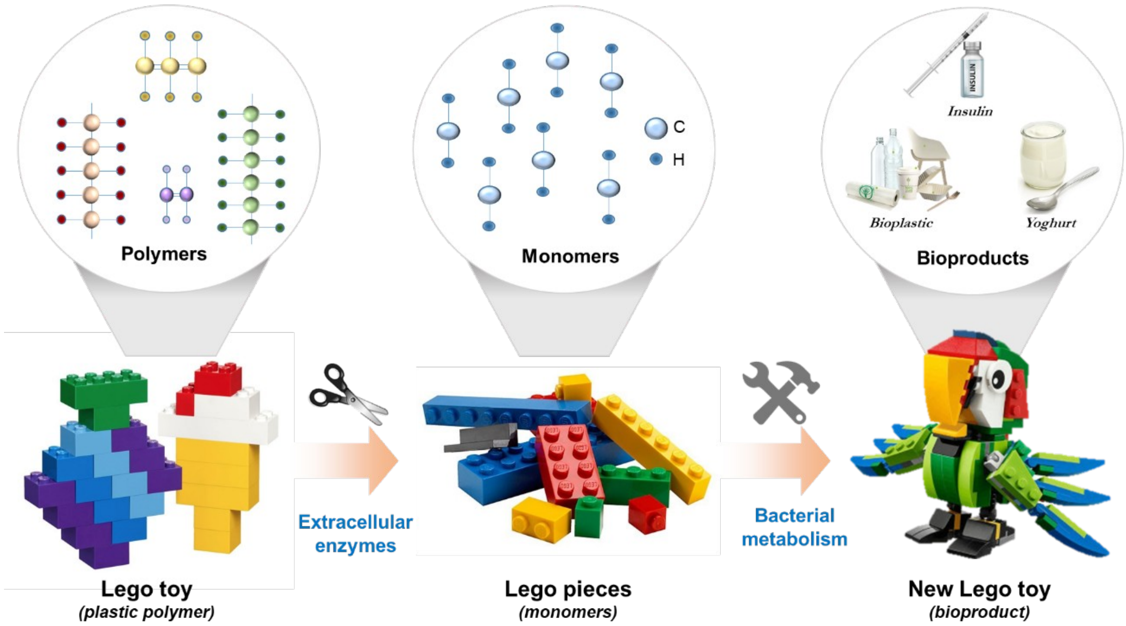

Figure 5. Scheme for the ideal transformation of plastic polymers based on a Lego analogy. Basic polymer and monomer structure. C and H represent carbon and hydrogen atoms.

These enzymes are particularly interesting to industry, as they can be engineered to domesticate microorganisms to carry out plastic degradation in confined systems after sorting. The mission of biotechnologists is to improve these enzymes, increasing production and improving their degrading power and effectiveness, so that they can be utilised in recycling processes. To achieve this, they use synthetic biology instruments to genetically modify the bacteria responsible for expressing and producing these enzymes. This allows them to enhance the performance of individual enzymes, boosting their degrading speed, increasing their extracellular secretion, or changing their specificity to recognise a new target polymer.

Biotechnology and synthetic biology also open up a range of new possibilities. Would it be possible to develop a new material to replace some plastics?

6. Petroleum-based plastics could be partially replaced by similar materials that will not be so harmful for the environment. New materials based on renewable raw substances, called **bio-based plastics (BBP)**, are currently being developed and starting to be used. If these materials are to replace traditional plastics in some applications like food packaging, they need to have similar properties. There are many different kinds of traditional plastics made from petroleum, which is a non-renewable source. The key traits they all share are a high capacity to deform without breaking, wetting resistance strength and low production cost. In order to replace standard plastics with alternative materials, these must offer the same properties and also be environmentally friendly.

BBPs are produced from renewable sources, such as plant waste, industrial waste or urban residues, and they can be either **biodegradable (and/or compostable)** or **non-biodegradable**:

- Non-biodegradable BBPs can be chemically identical to petrochemical plastics, as with **polyethylene** (bio-PE) and **polyethylene terephthalate** (bio-PET), but the fact that at least one of their components is made from organic matter derived from renewable resources makes their production independent of unsustainable systems. Their synthesis involves the chemical modification of bioethanol produced by biotechnological processes. For all their excellent properties, however, non-biodegradable BBPs still represent a challenge for the environment as far as they need recycle treatments similar to those of the oil-based counterparts.

-Biodegradable/compostable BBPs, on the other hand, are efficiently degraded by microorganisms when grown under controlled conditions of light, humidity and temperature in recycling or composting plants (compostable BBPs). Some of them are as well biodegraded in some sites of the open environment (biodegradable BBPs) but it depends on the abiotic conditions and microbial diversity of the particular place. The most widely used compostable BBPs today are made from potato or cereal starch and **polylactic acid** (PLA). PLA is synthesized in two stages: first, lactic acid is generated by bacterial fermentation from corn or beet waste, and then PLA is chemically synthesized from lactic acid by a conventional reaction used by polymer chemists called ring-opening polymerization. Plastic bags are being replaced in large quantities by bags made with potato starch, and PLA is replacing traditional plastics used in food packaging.

There are other biotechnological strategies consisting of using other microbial biopolymers such as **bacterial cellulose** or **polyhydroxyalkanoate** (PHA) to generate BBPs. PHA has been the fastest growing material on the market in recent years, although it is still difficult to find products made from this polymer. PHA is a BBP directly produced by many bacteria. It is the only plastic material that is entirely generated by a living organism. These bacteria are able to feed on waste and transform it into intracellular fat inclusions called PHA granules, which are stored inside their cytoplasm as a carbon and energy reserve, similarly to the way human beings build up fat reserves. This enables PHA to be produced from wastewater obtained in treatment plants, from urban refuse and even from gas streams (e.g. CO_2 and/or CO) generated in thermochemical processes, such as gasification and pyrolysis. The properties of the resulting PHA will vary depending on the substrate on which the productive bacteria are fed, so biotechnologists choose an appropriate culture medium in which to grow the bacteria and combine it with the relevant genetic modifications to obtain the tailored BBP they are looking for.

Last but not least, the fact of replacing conventional plastics by BBPs does not imply that the concept of **6 Rs** is not valid anymore. If we aim for BBPs utilization in our daily life, it will require proper fabrication and waste management systems. Just to do it better this time.

Replacement of traditional plastics with alternative, renewable, BBPs is still a long way away, but there has been a clear shift in terms of manufacture and applications towards these materials. The properties offered by these materials, either individually or combined, are on a par with those of modern plastics.

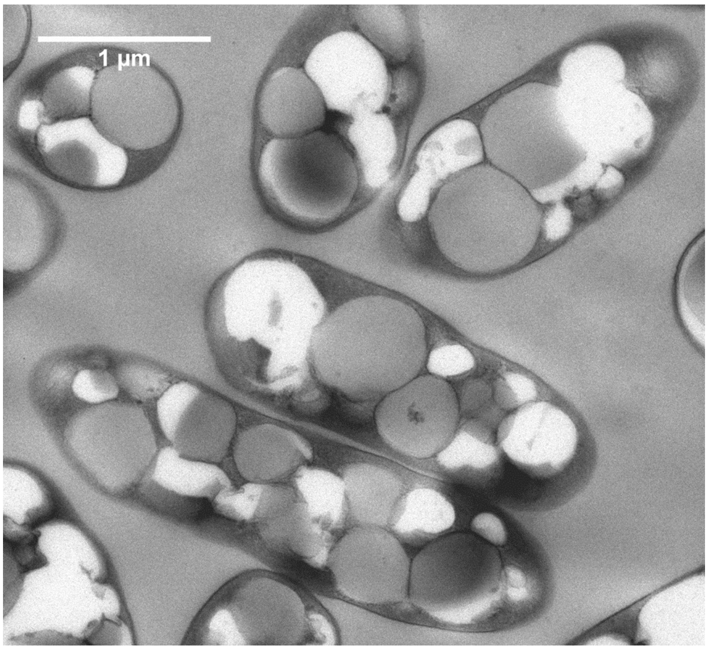

Figure 6. Electron micrograph of PHA-producing bacteria. The granules inside the cells are mostly composed of PHA polymers.

Relevance for Sustainable Development Goals and Grand Challenges

Plastic pollution issue and bioplastics related to several SDGs.

- **Goal 3. Ensure healthy lives and promote wellbeing for all at all ages** *(improve health; reduce preventable disease and premature deaths).* The life cycle of plastics generates massive amounts of waste, which is often released into the air and water in the environment. These microplastics and toxic chemical compounds are indirectly inhaled or ingested by human beings, seriously affecting their health. These plastics could be replaced by new non-petroleum-dependent, biodegradable, biocompatible materials, such as microbial plastics, which are more environmentally friendly and therefore potentially less harmful to people's health.

- **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, and improve water and sanitation management).* Most petrochemical plastics have chemical additives and metals on their surface. As these plastics degrade in the oceans and rivers, they release pollutants that are toxic to human health. These pollutants end up in the sea animals that people eat, and in groundwater sources, impairing the quality of drinking water.

- **Goal 11. Sustainable cities and communities** (*make Cities and Human Settlements Inclusive, Safe, Resilient and Sustainable).* Recycling and proper management of plastic waste, together with a strategy based on replacing petrochemical plastic with bio-based plastic, will lead to better conservation of the environment and recovery of habitats that have already been compromised by this type of waste. These improvements will result in healthier environments.

- **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, and inform people about sustainable development practices).* Current production and consumption of plastics is unsustainable and has an extremely high impact on ecosystems. Huge amounts of plastic are produced which cannot be properly managed by recycling alone. We need to work towards sustainable, responsible production and consumption. We need to replace single-use materials as far as possible with biotechnologically designed materials that are biocompatible, durable, recyclable and obtained from cheap raw materials, including waste.

- **Goal 13. Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, and improve education about greenhouse gas production and global warming).* The production and incineration of plastics releases gases including CO_2, CO, H_2, CH_4 and N_2O. Throughout their life cycle, plastics contribute to increases in greenhouse gases entering the atmosphere. This environmental impact could be reduced by encouraging the recycling and reuse of materials, as this would avoid incineration as a method of waste management and reduce plastic dumping on beaches and landfills. Besides, biotechnology makes it possible to generate microorganisms that are able to use these greenhouse gases as "food" for bacteria, which can then produce bio-based plastics. This achieves two goals: (i) no greenhouse gases are released by waste incineration, and (ii) BBPs are produced to gradually replace petrochemical plastics.

- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development** *(reduce pollution of marine systems by toxic chemicals/agricultural nutrients/wastes like plastics, develop mitigation measures for acidification, and enhance sustainable use of oceans and their resources).* Between eight and twelve million tonnes of plastic, such as bottles and bags, end up in our oceans every year due to poor waste management. These plastics are directly responsible for the deaths of many sea animals and birds. The chemical additives and heavy metals contained in these plastics are toxic to marine ecosystems. Controlling the source of plastic waste generation and investing in environmental education could reduce ocean pollution.

Potential Implications for Decisions

1. ***Individual***
    a. Should we use BBPs or petrochemical-based plastics? Does their lower environmental impact compensate for their higher cost and the need to adapt recycling/composting chains to these new products?
    b. Should we continue to use single-use plastics or is it preferable to use reusable plastics? Do the environmental benefits of reducing the production of single-use plastics outweigh the health and hygiene benefits they provide? Could this depend on the setting in which such plastics are used?
    c. Is it better to buy food in plastic packaging or loose? Eliminating packaging reduces plastic waste and decreases the carbon footprint. Do these benefits outweigh food safety and longer shelf lives?

2. ***Community policies***

a. Implement education and awareness programmes.
b. Provide and manage suitable containers for recycling and composting.
c. Produce descriptive and explanatory literature on the different types of BBPs, focusing on their individual characteristics, compostability and recyclability.

3. National policies relating to BBPs

a. BBP management: Can the same recycling chain continue to be used or is it necessary to open new lines for BBP management? Establish the cost of these strategies.
b. Specific labelling by type of plastic or BBP.
c. Labelling of containers and packaging for proper waste collection and management.
d. Align waste management regulations and procedures across different countries and regions.
e. Should farmland be used to produce BBPs or should their production continue to be based on waste recovery?
f. Taxation of companies that produce non-eco-friendly plastics.
g. Regulation of the production and marketing costs of BBP-based products.
h. Determine the environmental impact of BBPs from the beginning to the end of their lifetime.
i. Assessment and report on the environmental impact of BBPs and microplastic pollution in rivers and oceans.
j. Production of greenhouse gases in plastic waste management processes.
k. Control of additives and toxic metals in the production of BBPs.

Pupil Participation

1. **Class discussion of the issues associated with plastics**
    a. Impact of plastics in the oceans.
    b. Impact of plastics in the human health.
    c. Class discussion of BBPs as an alternative material.

2. **Pupil stakeholder awareness**
    a. Plastics: positive and negative consequences for the SDGs. Which of these are most important to you personally?
    b. BBPs have positive and negative consequences for the SDGs. Which of these are most important to you personally?
    c. Can you think of anything that might be done to reduce the negative consequences of plastics, especially in the food/packaging industry?
    d. Can you think of anything you might personally do to reduce the environmental footprint of plastics?

3. **Exercises**
    a. In most cities, plastic/BBPs waste management is either ignored or handled as regular garbage. What other alternatives to disposing plastic waste can you envision?

b. Plastic materials are produced in large facilities, often connected to automobile, construction and food processing operations. What sustainable options are there for cars, buildings and packaging? How might you formulate a sustainable car, food, and produce it for your city/town/region?
c. Looking at the SDGs, how can we change our approach to plastic companies to bring them into sustainable living? What are the challenges and opportunities?
d. Create a sustainable city plan for plastic production and their associated environmental impacts.

4. **Class experiments**
    a. The students in the class collect different types of BBPs and place them in different environments for weeks or months (e.g. bury them in the school playground). Every week they take samples and observe the degradation of the different kinds of BBPs.
    b. Compare different types of BBPs. Try to distinguish between a PLA bottle and a PET bottle with no prior knowledge of what each one is made of.
    c. What kind of material would you like to have? What would it be like? Describe the properties it would have and what other materials you would make it with.

The Evidence Base, Further Reading and Teaching Aids

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- Narancic *et al.* Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but They Are Not a Panacea for Plastic Pollution. *Environ. Sci. Technol.* (2018) 52, 10441−10452. DOI: 10.1021/acs.est.8b02963
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- https://www.eea.europa.eu/airs/2018/resource-efficiency-and-low-carbon economy/greenhouse-gas-emissions)
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- https://www.ciel.org/wp-content/uploads/2019/02/Plastic-and-Health-The-Hidden-Costs-of-a-Plastic-Planet-February-2019.pdf

Glossary

- **Additives:** Organic and inorganic compounds and substances mixed into or applied to the surface of plastics to bestow desired material properties on the plastic. For instance, antioxidants, binders, colourants, flame retardants, plasticisers, reinforcements, stabilisers, etc.
- **Bioaccumulation:** Gradual accumulation of an organic compound, such as pesticides, in an organism. Bioaccumulation occurs when an organism absorbs a compound at a rate higher than that at which the compound is lost from the organism.
- **Bio-based plastic:** Plastic containing organic carbon of renewable origin from plant, animal or microbial sources.
- **Biodegradable plastic:** A plastic that undergoes biodegradation involving the metabolic utilization of the plastic carbon by microorganisms such as bacteria, fungi, and algae resulting in the conversion of plastic carbon to CO_2 (and CH_4) and microbial biomass.
- **Bioplastic(s):** A generic term that subsumes both plastic materials composed of biodegradable polymers as well as plastic materials composed of bio-based polymers.
- **Biopolymer:** A polymer produced by a living organism.
- **Enzyme:** A protein produced by a living organism that helps a chemical change happen or happen more quickly, without being changed itself**.**
- **Microplastic:** Extremely small pieces of plastic in the environment that come from consumer products and industrial waste.
- **Plastisphere**: Thin layer of microbial life that surrounds plastic in aquatic environments. It occurs on every one of the trillions of small pieces of plastic in the ocean. This miniature ecosystem includes primary producers using sunlight and inorganic chemicals to grow, grazers feeding on these "fields" of primary producers, predators killing and eating other cells, parasites, symbionts living together with their hosts, and degraders recycling biomass and chemicals for reuse in the system.
- **Polyhydroxyalkanoate (PHA):** PHAs are biodegradable biopolymers and bio-based plastics, synthesized by many bacteria as intracellular product via microbial fermentation processes.
- **Polylactic acid (PLA):** PLA is a bio-based and industrial compostable polyester. It is formed by L and/or D-lactic acid that are produced via microbial fermentation and further chemically polymerized to yield PLA.
- **Waste Hierarchy:** It accounts for the EU's approach to waste management. It aims to adopt a waste hierarchy, which sets the following priority order when shaping waste policy and managing waste at the operational level: prevention, (preparing for) reuse, recycling, recovery and, as the least preferred option, disposal (which includes landfilling and incineration without energy recovery).

[1] https://www.sapea.info/topics/microplastics/

[2] This particular view of the plastisphere was designed by Rafael del Villar, a Biochemistry Grade student at UAM, Spain- The drawing of the plastic litter has been adapted from an image from Freepik.com (vector de Ola, created by upklyak, https://n9.cl/c7m7l)