Plastic Waste
Age range: 15 – 18 years

# PLASTIC RECYCLING TECHNOLOGIES

This lesson introduces students to the plastic waste recycling technologies that are available and under research and development, key aspects of the technologies and the challenges.

## LESSON OBJECTIVES

Students will be able to:

- Understand why plastics are recycled.
- Understand how plastics are recycled and the challenges.
- Understand the basic science and methods required for plastic production and recycling.

## STUDENT OUTCOMES

Students will:

- Learn about plastic material synthesis, polymer chemistry and properties.
- Understand why plastics waste is source of pollution and the need for recycling.
- Be informed about existing technologies/solutions to recycle plastic waste.
- Discuss new potential ways to tackle plastic waste.
- Explore and learn about new technologies for plastic waste recycling.
- Learn about challenges in recycling of plastics.

## SUMMARY OF TASKS

*Before undertaking this lesson, it would help students if they have been introduced to the plastic waste and mechanical recycling topics. This could be through the 'Introduction to the Plastic Waste' lesson plan.*

### PART 1 - INTRODUCTION

- Begin by splitting the students into groups of 3-5. Together they will brainstorm ideas for 5 minutes to answer the question; why does plastic waste cause pollution and what properties make plastic waste disposal difficult?
- Reconvene and share ideas with the class. Some example answers include the fact that plastics are rigid/durable and resistant to degradation/decomposition in environment, which makes them persist around for a long time. Guided by the fact sheet on 'Plastic recycling' summarise the ideas generated. The take home message should be that the composition and structure of plastic means it is hard to degrade. This results in an accumulation of plastic waste in the surrounding environment for a long time.

## PART 2 – DISSCUSION

- Using the fact sheet explain the structure and composition of plastics, how they are made, where plastics usually go after we use them and plastic disposal.
- Ask the students to go back to their groups. Give them 5 minutes to discuss potential ways to prevent accumulation of plastics waste in the environment and surroundings.
- Reconvene and share ideas with the class. It is important students have an appreciation for the role of plastic recycling in tackling the issue of plastic waste and its accumulation in the environment.

## PART 3 – APPLICATION

- Ask the students to complete the 'Plastics Chemistry & Chemical Recycling' activity sheet in their respective groups; where they can suggest ways to recycle plastics and remove plastic pollution from the environment.
- The homework suggested offers independent work if that is more appropriate.

## RESOURCES/ EQUIPMENT

- 'Plastic Waste Recycling' Fact Sheet
- 'Plastic Chemistry & Chemical Recycling' Activity sheet
- 'Plastic Making & Chemical Recycling' Homework sheet

## HOMEWORK/ EXTRA ACTIVITIES

Upon completion of the activities, further learning on plastics recycling technologies is encouraged via an appropriate homework task.

- Ask students to write a short essay (3-4 paragraphs) summarising the plastic waste problem, the role of plastics recycling, and available technologies for plastic recycling.

# FACTSHEET: PLASTICS WASTE RECYCLING

FACT SHEETS HAVE BEEN DESIGNED FOR TEACHER USE TO AID CREATING OF TEACHING RESOURCES, OR THEY ARE FREE TO BE REPURPOSED FOR STUDENT USE.

## PART 1 – SCIENCE OF PLASTICS

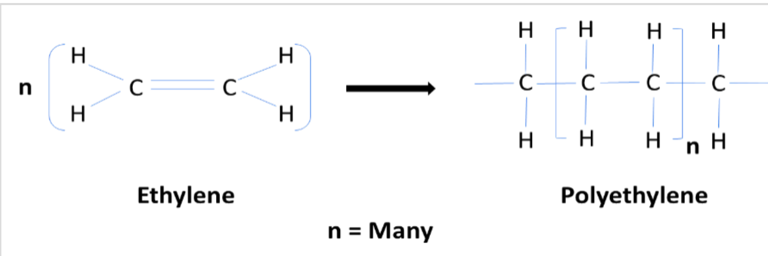
### Properties

Plastics are materials which are malleable, during manufacturing they can be moulded into different shapes, such as films, fibres, plates, tubes, bottles, etc. Their composition is mainly of polymers (main matrix); and to this base material a variety of additive compounds can be added to make the end plastic product. These additional compounds offer extra properties/functions to the material, such as preventing oxidation, adding colour, rigidity, reduce flammability etc. Additions of these compounds are not an essential part of the plastic material definition, but these additives are important for the performance and function of the plastic product. Plastics are stable materials and very durable, it is this property that allows them to persist in the environment after they deliver their intended function. This property in addition to the content/composition of the plastic material results in plastics becoming a source of natural pollution.

### Synthesis

The main component of plastics, the polymer, is synthesised using a chemical reaction known as polymerisation. This reaction creates many linkages between repeating small molecules (known as monomers – 'mono' = one and 'mer' = part) to make a polymer (poly = many, 'mer' = part). There are different modes of polymerisation. Addition polymerisation is simply joining monomer units together to make a larger molecule (polymer). Condensation polymerisation involves the formation of the polymer via a condensation reaction, joining the two molecules together results in the elimination of a small by-product molecule, such as water or methanol.

For example, polyethylene (PE) is formed using addition polymerisation, this plastic is used for plastic bags. The structure of PE is a long, repeating sequence of ethylene monomers linked together as seen below. Other plastics formed using addition polymerisation include, polypropylene (PP), polyvinyl chloride (PVC) and polystyrene (PS).



Examples of plastics that are formed using condensation polymerisation include, polycarbonate (PC), polyamides (such as Nylon) and polyesters (such as polyethylene terephthalate (PET) which is shown in the diagram below).

$$\mathbf{n}\,(C_2H_6O_2) \quad + \quad \mathbf{n}\,(C_8H_6O_4) \xrightarrow{-\,\mathbf{n}\,(H_2O)} (C_{10}H_8O_4)_{\mathbf{n}}$$

| Ethylene Glycol | Terephthalic Acid | Polyethylene Terephthalate (PET) |
|---|---|---|

## PART 2 – RECYCLING TECHNOLOGIES FOR PLASTIC WASTE

### Plastic recycling

The majority of plastic materials are made from six common polymers: polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyurethane (PU). Products made of each type of these materials are identified with a plastic recycling symbol as shown in the table below.

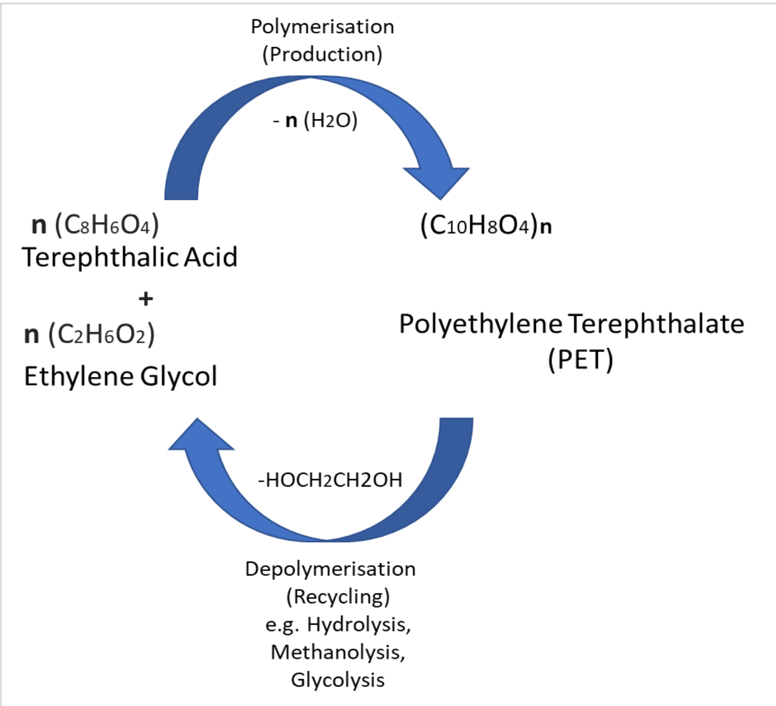
Plastics are very useful materials and have many applications, recycling can help dispose of used plastics while also generating new plastic material. The recycling of plastics can be a physical process (mechanical recycling), where only the physical structure of the plastic is affected. Recycling can also be chemical or biological, where the chemical structure of the plastic is changed. Mechanical recycling involves processes such as cleaning/washing, grinding, shredding and melting. While mechanical recycling is easy and common, it is applicable to all plastics and usually this recycling process produces low quality recycled material that cannot be used for its original application. The physical stress to the material degrades the mechanical properties of the recycled material, this eventually results in the recycled material being landfilled after repeated cycles of mechanical recycling.

### Chemical plastic recycling

Chemical recycling breaks down the plastic material into useful chemical compounds (gases, liquids, and solids) usually in the presence of a chemical agent (solvent). The recycled products made during chemical recycling can be used as a feedstock for chemical manufacturing and allows the plastic to be repeatedly recycled. These compounds can be either the building blocks of the plastic material (monomers, dimers and trimers), in which case these can be used again in the production of plastics. The reverse process of polymerisation (plastic production) is termed depolymerisation, which can occur to produce these building block chemicals. This is the reverse reaction, starting with the polymer molecule and resulting in the individual chemical components (monomers). Alternatively, the recycled products can be other feedstock chemicals, which can be repurposed within the chemical industry for other manufacturing/synthesis applications. The advantage of this method is that it normally produces chemicals of a high quality and allows valorisation of the plastic waste material.

Examples of chemical recycling processes include thermo-chemical processes such as pyrolysis. This method heats the plastic under an inert atmosphere, with no other chemicals present and produces gases, liquids, and solids. Alternatively, chemical solvents can be used to dissolve and break down the plastic. For example, water, alcohols, glycols, supercritical fluids, ammonia and amines can all be used as chemical solvents. This type of chemical recycling is generally known as solvolysis, but more specifically its name can relate to the solvent used. For example, hydrolysis is with water, methanolysis is with methanol, aminolysis is with amines, ammmonolysis is with ammonia and glycolysis is with glycols. Chemical recycling processes can be carried out without catalysts; however, catalysts can be used to facilitate decomposition of the plastic and reduce the amount of energy used.

Plastic that contains particular bonds or function groups within their chemical structure, such as ester groups with a O=C-O bond, can undergo chemical degradation reactions with solvents due to presence of these reactive groups in their structures (shown in the diagram below). These reactive bonds are easier to break than the C-C bonds present in the structure of many plastic materials such as polyethylene and polypropylene. During the chemical recycling process the ester bond is cleaved, and a new bond is formed by substitution producing useful chemical compounds.

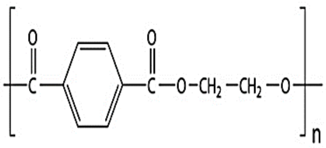
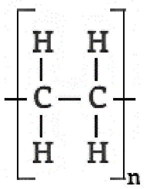
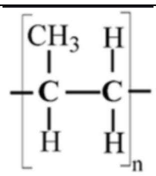
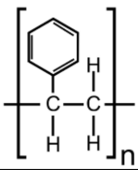
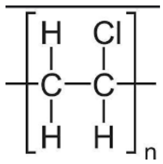
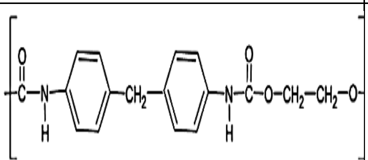
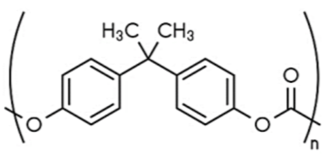



## Biological plastic recycling

Biological recycling is an emerging plastic waste recycling technology. This refers to the use of biological microorganisms, such as fungi and bacteria, and enzymes to break down plastic material and produce valuable chemical compounds. In these processes the biological material is able to make use of the plastic within its biological processes. This type of recycling is not commonplace yet; and research into these recycling methods is still developing.

Plastic Waste
Age range: 15 – 18 years

The table below describes a number of plastics, with their chemical structure, recycling symbol, common applications and potential recycling method(s).

| Plastic Name | Structure | Recycling Symbol | Application /Product | Potential recycling method(s) |
|---|---|---|---|---|
| Polyethylene Terephthalate (PET) |  | 1 | Water bottles | Mechanical recycling<br>Chemical recycling:<br>Solvolysis<br>Hydrolysis<br>Glycolysis<br>Methanolysis |
| Polyethylene (PE):<br><br>High-Density (**HD-PE**)<br>Low Density (**LD-PE**) |  | 2<br><br>4 | Milk bottles (HDPE)<br>Carrier bags (LDPE) | Mechanical recycling<br>Chemical recycling:<br>Pyrolysis |
| Polypropylene (PP) |  | 5 | Caps on ketchup bottles | Pyrolysis |
| Polystyrene (PS) |  | 6 | Yoghurt pots<br>Styrofoam | Pyrolysis |
| Polyvinyl Chloride (PVC) |  | 3 | Drainage pipes | Pyrolysis |
| Polyurethane (PU) |  | N/A | Electrical cable sheathing | Mechanical recycling<br>Chemical recycling:<br>Pyrolysis<br>Hydrolysis |
| Others (e.g; Polycarbonate) | Polycarbonate<br> | 7 | Polycarbonate:<br>Safety glasses, electronics, & shatterproof windows | Mechanical recycling<br>Chemical recycling:<br>Hydrolysis<br>Pyrolysis etc<br>Biological recycling:<br>Enzymes |

## Recycling Challenges

Sorting the plastic waste and separating the different types of plastic makes plastic recycling very challenging. Plastic waste materials are normally mixed (different types of plastics/polymers) and contaminated with other compounds. This makes it difficult to recycle the plastics using one process, as different types of plastic materials need different types of processing (not one size fits all usually).

Additionally, the chemical structure of the plastic material presents challenges. This is a factor as to how easily the polymer structure is broken, which determines how easy or challenging the recycling process will be. For instance, plastics which contain functional groups of dissimilar atoms (ester or ether groups) in their structure such as in polyesters (PET) undergo chemical reaction with solvents and break relatively easily. In contrast, plastics which contain mainly C-C bonds in the polymer backbone (such as PE, PP, PS) are harder to break down due to high activation energy of the C-C chemical bond. The carbon-carbon (C-C) bond is very stable, as electrons in this bond are shared equally between the two atoms of similar electronegativity. Bonds such as C-O (carbon-oxygen) are more polarised as the bond electrons are more attracted towards the more electronegative atom (oxygen in this case). Therefore, the bond is less stable and can be easily broken (low activation energy of reaction). Plastics such as PE, PP, PVC, and PS are recycled mainly via pyrolysis where high temperatures are required during the recycling process; mainly due to the high energy requirements to break the C-C bond. In contrast, PET which contains an ester group can be chemically recycled via reaction with different solvents at relatively low temperatures, due to the presence of the reactive ester group in its structure.

Plastics contain a mainly carbon backbone (C-C chain) and have high melting points. Therefore, chemical recycling process of plastics usually require use of high temperatures and the application of high pressures in some cases. Some processes use catalysts to lower the activation energy of plastic decomposition reaction and allow easier degradation. Some of the catalysts used are expensive and have limited cycle times. All of these factors increase the cost of the recycling process and make the final product more expensive.

Another challenge in chemical decomposition of plastics is the environmental impact of the chemical processes, which needs to be minimised. This includes for instance, reducing harmful emissions, and using renewable and less harmful and non-toxic chemical agents in the processes. The research and development efforts in the recycling processes of plastics focus' on efficiency, sustainability, and cost-effectiveness.

# ACTIVITY: PLASTICS CHEMISTRY & CHEMICAL RECYCLING

## Instructions

*Please see the web page for more information about plastic waste material and recycling.*

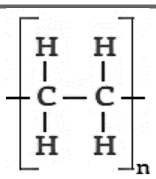
This activity is intended to introduce the chemistry of plastics and relation to chemical recycling of plastic.

This activity is intended to be used alongside the 'Plastic Recycling Technologies' lesson plan. The students should be shown the fact sheet within this lesson plan to help them complete the activity.

Task

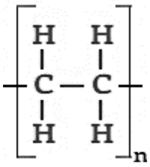
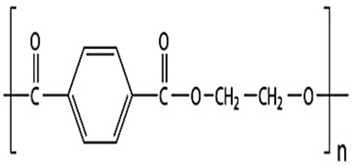
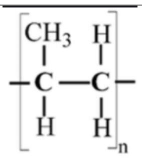
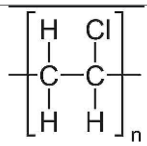
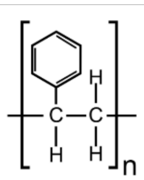
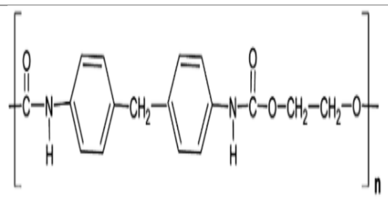
*If you are based in a classroom:*

Ask the students to have a discussion in groups about the chemical structure/composition of the plastic material and challenges associated to recycling these plastics based on their chemical structure. It could be helpful to think about actual products made of these plastic materials (refer to the table in the fact sheet) and their physical characteristics as well during discussion. Ask students to fill the following table to aid their discussion.

| Plastic Material | Structure | Chemical Formula | Key Bonds | Functional Group | Recycling challenge (examples) |
|---|---|---|---|---|---|
| PE |  | $(C_2H_4)_n$ | C-C<br>C-H | N/A | High activation energy to break C-C bond = High energy requirements |
| PET | | | | | |
| PP | | | | | |
| PVC | | | | | |
| PS | | | | | |
| PU | | | | | |

Plastic Waste
Age range: 15 – 18 years

## Completed Copy of Activity Sheet

| Plastic Material | Structure | Chemical Formula | Key Bonds | Functional Group | Recycling challenge (examples) |
|---|---|---|---|---|---|
| PE |  | $(C_2H_4)_n$ | C-C<br>C-H | N/A | High activation energy to break C-C bond = High energy requirements |
| PET |  | $(C_{10}H_8O_4)_n$ | C=O<br>C-O<br>C-H<br>C-C | -(O=C)-O- | High temperature and pressures |
| PP |  | $(C_3H_6)_n$ | C-C<br>C-H | N/A | High activation energy to break C-C bond = High energy requirements |
| PVC |  | $(C_2H_3Cl)_n$ | C-C<br>C-H<br>C-Cl | -Cl (Chloro) | Presence of Chlorine gives rise to formation of hydrochloric acid which is corrosive to recycling equipment |
| PS |  | $(C_8H_8)_n$ | C-C<br>C-H | N/A | Low weight of polystyrene and presence of contaminants |
| PU |  | $(C_3H_8N_2O)_n$ | C-C<br>C-H<br>C-N<br>N-H<br>C-O<br>C=O | −NH−(C=O)−O− (Urethane) | Producing poisonous gases by decomposition such as $NO_x$ and $CO_2$ gases |

# HOMEWORK: PLASTICS MAKING & CHEMICAL RECYCLING

## Instructions

*Please see the web page for more information about plastic waste.*

These activities are intended to help the student understand properties of the most common plastic materials, how they are manufactured and recycled.

They will highlight chemical recycling of plastics; its different classes and recycling methods applied in industry and in research for plastics waste recycling; and point out some of the useful products and associated challenges.

These activities are more beneficial to be set as homework so the student can familiarise themselves with the making and chemical plastic recycling of plastics.

### Task

Carry on an online research exercise on plastics and chemical recycling of plastics and complete the following two activities.

Useful online resources:

- https://chem.libretexts.org/
- https://omnexus.specialchem.com/selection-guide/polyethylene-plastic
- https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020
- https://www.plasticsinsight.com
- https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx
- https://www.plasticsrecyclers.eu/chemical-recycling
- https://www.chemicalrecyclingeurope.eu/

Plastic Waste
Age range: 15 – 18 years

ACTIVITY - 1

Fill in the following table.

| Plastic | Polymerisation Type | Production (million tonnes/year) | Common Chemical Recycling Method(s) | Chemical Feedstock from Recycling | Recycled in UK? | |
|---|---|---|---|---|---|---|
| PET | Condensation polymerisation | 30.3 (2017) | Hydrolysis Methanolysis Glycolysis | Terephthalic acid (TPA) & Ethylene Glycol (EG) | **Yes** | No |
| PE | | | | | | |
| PP | | | | | | |
| PVC | | | | | | |
| PS | | | | | | |
| PU | | | | | | |
| Polycarbonate (PC) | | | | | | |

ACTIVITY - 2

Common chemical recycling methods/processes based on the use of chemical solvents include: Hydrolysis, alcoholysis (eg: methanolysis), ammonolysis, aminolysis, and glycolysis. The most common ones in use in industry are *methanolysis* and *glycolysis*. Explore these two chemical recycling processes in your own time and answer as many of the following questions as you can:

- What are the chemicals used in each method?
- What are the advantages and disadvantages/challenges of each method?
- Do either of the methods require a catalyst? If so, mention an example of a catalyst used.
- Mention one example of a plastic material recycled via each method/process.
- Name some of the chemicals produced in these processes.