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AFRICAN RESOURCE BOOK: A GUIDE TO PLASTICS

CHAPTER 1

Plastics: Their properties and applications

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Plastics, as we know them today, are synthetic, malleable polymers derived predominantly from petrochemicals. Plastic polymers are fascinating. They are incredibly versatile and useful in modern life, but what makes them so beneficial can also damage people and the environment when handled incorrectly. We must understand plastics to eliminate their harmful effects while we harness their strengths. In this chapter, we unpack the more common plastics' types, properties, and applications while exploring the chemistry that gives them specific characteristics. We also dive into the world of "bioplastics" and clarify some misconceptions about these materials.

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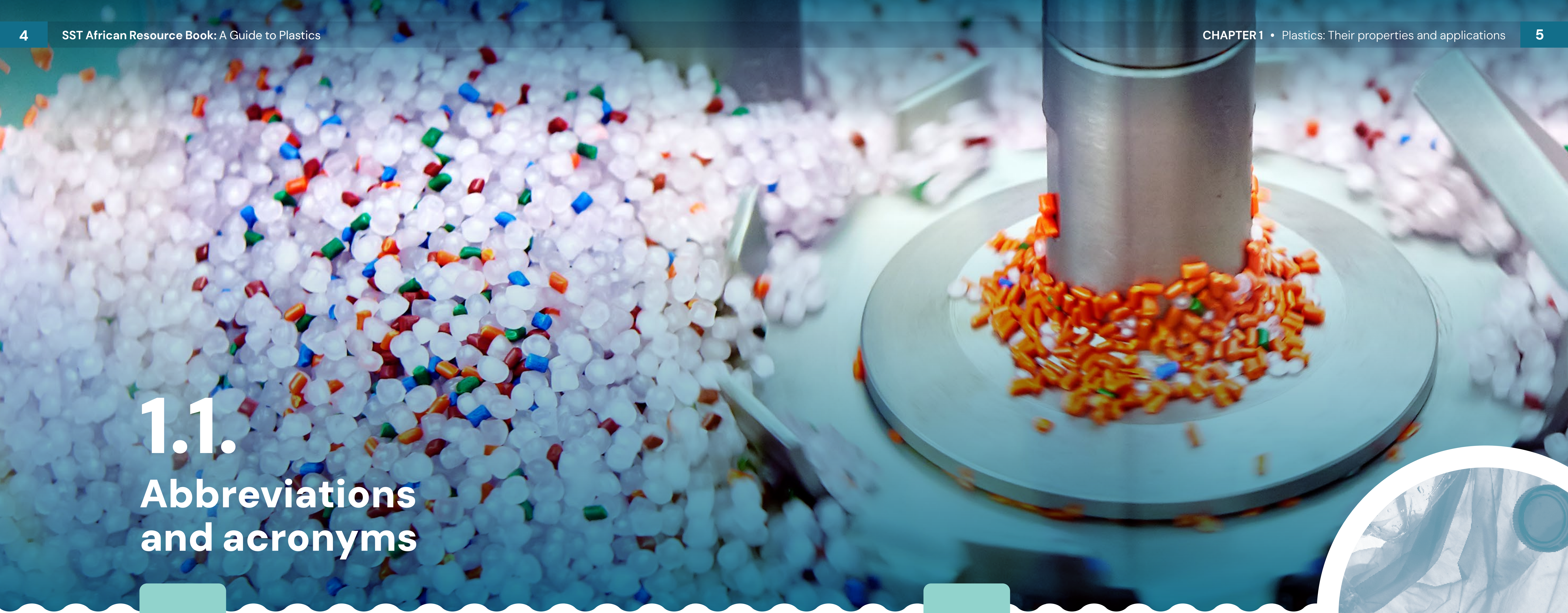

1.1.

Abbreviations and acronyms

ABS	acrylonitrile/butadiene/styrene
APET	amorphous PET
ASTM	Previously known as the *American Society for Testing and Materials*, it is now a registered name for the standards organisation
CO_2	carbon dioxide
CPET	crystalline PET
DMC	dough moulding compound (prepreg used in UP processing)
EP	epoxies
FRP	fibre reinforced plastics/polyesters
GRP	glass reinforced plastics/polyesters
MIC	material identification code
N_2	nitrogen
PA	polyamide, also called nylon
PC	polycarbonate
PE-HD	high-density polyethylene
PE-LD	low-density polyethylene
PE-LLD	linear low-density polyethylene
PET	poly(ethylene terephthalate)
PETG	poly(ethylene terephthalate) glycol
PMMA	poly(methyl methacrylate)
POM	polyoxymethylene, also called acetal
PP	polypropylene
PS	polystyrene
PS-E	expanded Polystyrene
PS-HI	high Impact Polystyrene
PVC	poly(vinyl chloride)
rPET	recycled PET
SAN	styrene/acrylonitrile
SMC	sheet moulding compound (prepreg used in UP processing)
UP	unsaturated polyester
UV	ultraviolet light

1.2.

Introduction

Over the last century, plastics have offered pioneering solutions to society's ever-changing needs and challenges. Versatile, durable, and incredibly adaptable, plastics are a group of remarkable materials with science and innovation at their core. Nowadays, they allow us to meet a myriad of functional and aesthetic demands, from drinking clean water, playing sport, staying connected, enjoying the comfort of home and the efficiency of clean mobility to helping us live longer and healthier lives.

The run-up to plastics, as they are known at present, began in the second half of the nineteenth century with modified natural materials such as vulcanised fibre (1859), cellulose nitrate (1869) and casein-based plastics (1897). The first fully synthetic polymer was phenol-formaldehyde, which appeared in 1908. This was followed by a flood of plastics, which changed the world as we know it today, and new advances are still being made.

Plastics are incredibly diverse. Due to the development of new materials, better processing methods, and greater possibilities in the manufacture of processing machinery, at least 45 different polymers are currently commercially available. Synthetic fibres, adhesives, paints, and coating resins are not considered plastics in everyday language, although they technically meet the criteria of what makes a plastic.

Plastics will continue to shape our present and future. However, we will only be able to achieve their full potential if we address the global challenges linked to their negative impact, particularly when they end up in the environment as pollution. We need to understand them properly to eliminate their harmful effects while we harness their strengths. Therefore, this chapter explores plastics' properties – sometimes delving into the chemistry - and describes the various categories and types available today. This chapter relies heavily on the works of Woebcken (1995) and Schwarz et al. (2005) unless otherwise cited.

1.3.

Defining plastics

1.3.1. WHAT ARE PLASTICS?

As the word "plastic" implies, the various types share one important property: they have plasticity or malleability. That is, the ability to be formed or shaped (Figure 1.1).

Figure 1.1: *Plastic implies plasticity.*

Broadly speaking, plastics are a group of materials, either synthetic or naturally occurring, that may be shaped when soft and then hardened to retain their given shape. This characteristic has helped make plastic as ubiquitous and diverse as it is today.

The plastics we know today are typically synthetic polymers of high molecular mass[1]. The word polymer comes from two Greek words: *poly*, meaning *many*, and *meros*, meaning *parts* or *units*. A polymer can be thought of as a chain in which each link is the *"mer"* or *"monomer"* (the single units). Synthetic materials are man-made as opposed to naturally occurring materials such as wood, iron ore, stone, and sand.

Although most plastics are synthetic, they are also organic. In chemistry, organic materials include carbon (C) and hydrogen (H) elements. Plastics are produced from chemicals extracted from oil, gas, or even coal (and, in some cases, plant-based sources), which are all substances of organic origin. Therefore, we can define plastics as synthetic materials made from many repeated chains of organic molecules, which can then be formed into different shapes.

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[1] Molecular mass (or, more accurately, *relative* molecular mass) is exactly that: the mass of a molecule, i.e., the combined masses of the atoms, the building blocks, that make up that molecule and is calculated relative to the mass of a carbon-12 atom. So, this value does not have a unit (although scientists may use the unit dalton). The molecular mass of plastics is greater than 8 000.

1.3.2. PROPERTIES OF PLASTICS

Despite the large variety of plastics, they have several properties in common, including useful as well as limiting attributes.

Advantages of plastics

Why are plastics so ubiquitous in society? Their useful properties make them versatile and easy to mass-produce.

Plastics are lightweight
Plastic bottles, for example, are lighter than other materials. Therefore, the energy cost of moving them from the filling line to the shop and from there to the consumer is less than that of glass or metal containers.

Colourable
Colouring plastic products is easy and distinctive. The colour is part of the product, so if scratched, the outside colour still shows – unlike paint, which can flake off a surface.

Strength/mass ratio
Plastics have a high strength-to-mass ratio; they are exceptionally strong for their mass. This feature makes it an ideal material for fuel-efficient aeroplanes, blades for wind turbines, and racing car bodies. The humble carrier bag is a classic example of a thin, lightweight product with surprising strength.

Low energy consumption
From feedstock (the unprocessed materials used to produce plastic goods) to the final product, plastics typically require less energy to create than other materials. Thus, plastic products are comparatively more cost-effective (Pilz et al. 2010)[2]. Their properties are also such that they conserve energy while in use, as plastics are lighter than their alternatives. In contrast, others conserve heat energy because they are excellent insulators (see below).

Corrosion and chemical resistance
A plastic can resist corrosion by almost any known chemical. Plastics are also able to withstand surface deterioration much better than metals.

Insulation
Their thermal, acoustic, and electrical insulation (Figure 1.2), as well as vibration-damping properties, often make plastics the only choice for containing heat, sound, and electricity.

Figure 1.2: Plastic insulation makes electric cables safe to use.

Adaptability
Polymers and plastics can be easily modified and adapted to suit almost any application.

Recyclability
Theoretically, almost all types of plastic can be recycled, and there are well-established recycling systems in many parts of the world. If originally designed for recycling, new products or brands can just slot into a sustainable end-of-life solution. Exceptions include multilayered plastics that require specialised recycling technologies that are rarely available. Unfortunately, plastics are recycled much less than they theoretically could be.

Disadvantages of plastics

Plastics also have limitations, and some types are more suited for specific applications. In practice, many of these disadvantages can be overcome by modifying or using the correct plastic type for a particular application. Others are more difficult to overcome, resulting mainly from human behaviour and how we use and dispose of plastics.

Attacked by ultraviolet radiation
Plastics are photodegradable – sunlight, particularly in Africa, discolours, weakens, and eventually breaks down most polymers unless specially formulated.

Affected by extreme temperatures
The temperature range in which plastics can operate is narrow. As is true for all organic materials, both extremely cold and hot conditions cause plastic products to fail and even break down or degrade.

Creep
Under load and over time, especially at elevated temperatures, plastics' dimensions (shape) change.

Pollution
Plastics are visible when littered, in other words, when deposited into the environment rather than correctly disposed of. Plastics are the most conspicuous form of litter because they are often brightly coloured. More importantly, they generally do not biodegrade, as do plant material or food waste, even though they are organic. It is almost impossible for bacteria to break down plastic polymers, especially of large items, in cold environments or when hidden from the sun (see Section 1.4.4.). This means plastic pollution persists in the environment for long periods. Nevertheless, remember: *People litter, not plastics.*

Scratches
Plastics generally scratch easily (just ask anyone wearing spectacles).

Selective chemical resistance
Different plastics are resistant to different chemicals. Therefore, when materials are selected for packaging, the chemical composition of the contents must be considered carefully to ensure packaging performs optimally.

Poor oxygen, water, and gas barrier
Long-life food products are not stored in plastic packaging, as glass and metal provide superior barrier properties to oxygen, water vapour, and other gases.

Thermal expansion
When plastics are used in combination with other materials, especially metals, the thermal expansion rate must be considered for expected performances.

Misunderstood
The word *"plastic"* is sometimes used synonymously with *imitation* or *cheap* and may perform poorly in certain instances. However, this happens when the wrong material is used for a particular application due to incorrect product design or when something goes wrong during product manufacture. Unfortunately, many who design, select, and process these materials do not correctly understand the properties and nature of plastic. This results in poor-quality products, leaving the user with a negative impression of such plastics. The layman similarly does not understand plastics, creating false expectations or disappointment when the plastics fail or behave strangely.

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[2] See Pilz et al. (2010) here: https://plasticseurope.org/wp-content/uploads/2021/10/201009-Denkstatt-Report.pdf). See also Russo et al. (2020). Comparing Grocery Carrier Bags in South Africa from an Environmental and Socio-Economic Perspective. Evidence from a Life Cycle Sustainability Assessment. CSIR: Stellenbosch. (https://wasteroadmap.co.za/research/grant-022/).

1.3.3. MATERIAL IDENTIFICATION CODES

The material identification coding system (MIC), or polymer identification code (PIC), is a set of symbols placed on plastics to identify the polymer type.

The coding system was developed by the American Society of the Plastics Industry (SPI, now called the Plastics Industry Trade Association) but has been administered by ASTM International since 2008. This polymer coding system, known as ASTM D7611, is used internationally and identifies the main raw material used to construct a plastic product.

Different markings are used for packaging and non-packaging applications (Table 1.1). Packaging products are identified by a material identification code consisting of three chasing arrows in a triangle with a number inside (Figures 1.3A and B). The acronym for the polymer is placed underneath the triangle. The major packaging materials are identified with symbols 1 to 6. All other packaging is identified with a number 7, often with the word "other" beneath it or with the appropriate material acronym underneath. Since "other" is not a polymer and is uninformative as an identification code, an acronym specifying the polymer should be shown underneath the symbol. However, in practice, this is not always the case. Non-packaging plastic products should be marked at some place on the surface with the appropriate acronym set between ">" and "<" marks (Table 1.1).

Some symbols may cause confusion. The MIC for packaging materials should not be mistaken for the universal recycling symbol, the Mobius loop (Figure 1.3C). The Mobius loop, consisting of three chasing arrows, indicates that a product is recyclable. Remember that although most plastics are technically recyclable, they are only locally recycled if there is a suitable market for products made from recycled material and if recycling is economically feasible. Although the MIC looks quite similar to the recycling symbol, it does not indicate that the product can be or is readily recycled (and the number inside is no indication of how many times a product can be recycled either). While some plastic polymers are more readily or widely recycled than others, the polymer number primarily indicates polymer type. This information is, however, useful in allowing the efficient separation of plastic types into their appropriate recycling streams. Therefore, while both signs can inform recycling in one way or another, their primary function and the information they indicate are quite different.

Figure 1.3: *Example of material identification codes. A) The code for PP, one of the commodity plastics. B) Sometimes, a producer will indicate the identification codes for each part of the packaging (a water bottle in this case), i.e., the bottle, the lid, and the label. "BOPP" indicates PP with biaxial orientation (see Section 1.4). C)The Mobius loop.*

Table 1.1: *Various polymers, their material identification codes, and some product applications.*

Material	Packaging		Non-packaging	
	Material identification code	Product examples	Material identification code	Product examples
PET Poly(ethylene terephthalate)	01 PET	Carbonated drink bottles, mineral water bottles, clear bottles, clear jars, trays, and punnets for fresh produce and meat; clear films to package oxygen—and moisture-sensitive products; labels, blister packs; strapping tapes; vending cups[3]. The same code is used for CPET, rPET, and APET but **not** for PETG.	>PET<	Carpeting, fibres for apparel[4] and industrial applications; machined engineering components, e.g., bushes for drive shafts of large ocean liners; face mask sheeting; and geotextiles for soil protection and drainage of sports grounds.
PE-HD High density polyethylene	02 PE-HD	Milk bottles, fruit juice bottles, drums, packaging films, carrier-type shopping bags, tubs, caps and closures, bottles for personal and domestic care, crates, pallets, bins, and jars.	>PE-HD<	Irrigation pipes, shade cloth and shade netting, shopping trolleys, refuse and wheelie bins, high-pressure water pipes, optical fibre trunking, conveyor rollers, ventilation ducting, and automotive components.
PVC-P Flexible poly(vinyl chloride)	03 PVC	Cling film, pouches, cap liners, and see-through bags for toys, clothing, and bedding.	>PVC-P<	Cable insulation, gumboots, shoe soles, flooring, matting, medical cloth and tubing, tarpaulins, hoses, safety gloves, soft toys, and rainwear.
PVC-U Rigid poly(vinyl chloride)	03 PVC	Clear bottles, jars, blister packaging, tamper-evident neck seals on bottles and jars, shrink labels, thin films used for sweet wrappers and packets, and flower and gift wrapping.	>PVC-U<	Water pipes, high-pressure pipes, conduit, wood cladding, clear stationery sheeting, plumbing, skirting, cornices, trunking, cooling tower packing, window frame profiles, gutters, and downpipes.
PE-LD and **PE LLD** Low and linear low-density polyethylene	04 PE-LD	Packaging films, domestic cling wrap, stretch wrap, stretch labels, shrink wrap, bags, shrouds, dust covers, form-fill and seal packs, peelable lids, cosmetic tubes, boutique shopping bags, bubble wrap, and foam sheeting.	>PE-LD< and >PE-LLD<	Irrigation pipes, cable insulation, agricultural films, rotationally moulded products like tanks and corner protectors.
PP Polypropylene	05 PP	Yoghurt & margarine tubs, ice cream containers, bottles, caps and closures, canisters for storage, strapping tape, crates, buckets, jars, cups and vending cups[3], straws, takeaway cutlery[5], punnets. Flexible packaging including wrappers, woven bags, clear, crispy packaging films, metallised (printed) films, nonwoven cloth, shrink labels, and self-adhesive labels.	>PP<	Coat hangers, battery cases, bobbins and reels, automotive components, furniture, bowls and basins, carpeting, woven cloth for soil stabilisation and reinforcement in mines, non-woven cloth for crop protection and hygiene products such as nappies, baler twine, brush bristles, hair extensions, appliance housings for toasters and kettles, toilet seats, ropes, fishing nets, fibres for apparel[4] and industrial applications such as filter bags and strainers.

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[3] Take-away food containers and vending cups can be regarded as packaging as well as non-packaging. Containers and vending cups can be PP, PET, PVC, PS or PS-E.

[4] Although apparel fibres and textiles are included, apparel fibres are not part of the plastics industry per se but part of the textile and clothing industry.

[5] Cutlery can be regarded as packaging as well as nonpackaging and is made from PP, PS, ABS, or bioplastics.

***Table 1.1:** Various polymers, their material identification codes, and some product applications (continued)*

Material	Packaging		Non-packaging	
	Material identification code	**Product examples**	**Material identification code**	**Product examples**
PS and **PS-HI** Polystyrene (general purpose and high impact)	06 PS	Yoghurt portion packs (the small tubs), display boxes, clear trays, punnets, punnet lids, takeaway cutlery[5], stirring sticks, cake containers, dessert label sticks, vending cups[3], tumblers, vending cup lids, bread tags.	**>PS<**	Coat hangers, takeaway cutlery[5], throw-away crockery, toys, cups, plates, CD covers (transparent casing), computer and other electronics housings, cell phone covers, stationery items such as pens and rulers, fridge, and freezer liners.
PS-E Expanded Polystyrene	06 PS	Protective packaging, takeaway food containers[3], clamshell packaging, vending cups[3], punnets and trays.	**>PS-E<**	Insulation panels, suspended ceiling panels, seedling trays, mannequins, balls and other shapes for decoration, cooler boxes, cornices, skirting, Venetian blind slats, and louvres.
ABS Acrylonitrile Butadiene Styrene	07 ABS	Tubs, portion packs for margarine and jam, takeaway cutlery[5], glossy reusable tubs.	**>ABS<**	Textile cones, bobbins and reels, TV and other electronic housings, toys, automotive components, telephone casings, signage, metallised automotive components, metal lookalike items for building and construction, e.g., bath overflow, tap surrounds, reflectors for torches.
E/VAC Ethylene(Vinyl acetate)	07 E/VAC	Cap liners, sealing gaskets in clip-on lids for storage containers.	**>E/VAC<**	Foam insulation for exercise mats, comfort shoes, lightweight shoe soles, hand grips, cable insulation, and golf cart wheels.
Multilayer[6] PET and PA	07 PET+PA	Barrier PET bottles used for oxygen-sensitive products like wine, beer, and energy drinks.		*Generally, only used in packaging applications.*
Multilayer[6] PE and PA	07 PE+PA	Barrier films used as oxygen and moisture barriers for dairy and protein food stuffs – these materials often have more than two materials. Still, the two most prominent polymers are polyethylene and nylon.		*Generally, only used in packaging applications.*
Multilayer[6] PE and E/VAL	07 PE+E/VAL	Co-extrusion films or sheeting used in multilayer tubs, punnets, and trays for oxygen-sensitive contents like oily food or preservative-free fruits.		*Generally, only used in packaging applications.*
PA Polyamide or *nylon*	07 PA	Oven bags and barrier film in meat and dairy packaging—PA is seldom used as a packaging material alone.	**>PA<** **>PA GF15<**	Automotive components, fishing gut, cable ties, fibres for apparel[4], zips, plastic screws for hardware applications, tool handles for hammers and axes, housings for electric tools, and castors for chairs and ladders.
PC Polycarbonate	07 PC	Reusable water bottles.	**>PC<**	Lighting, lenses, automotive components, CDs and DVDs, reusable water fountain bottles, safety glasses, industrial sight glasses, wine- and beer tumblers.
PETG Poly(ethylene terephthalate) glycol	07 PETG	Personal care bottles manufactured in smaller volumes and non-symmetrical shapes *(small quantities).*	**>PETG<**	Thick sheeting used for structural thermoforming of containers, housing, and roof sheeting.
PMMA Poly(methyl methacrylate) or acrylics		*Not used as packaging material.*	**>PMMA<**	Signage, light covers, lenses, number plates, reflectors, automotive components, bathtubs, shower basins, mirrors, salad bowls, kitchen utensils, fibres for apparel[3] and bedding, e.g., synthetic wool.
POM Polyoxy-methylene or *acetal*	07 POM	Aerosol container valves.	**>POM<**	Stationery components, automotive components, curtain accessories, cigarette lighter components, and washing peg springs
PUR Polyurethane	07 PUR	Protective packaging for transport of valuable and sensitive articles. For example, glassware is placed inside a plastic bag, which is placed inside a much larger carton. The empty space is then filled with polyurethane foam from a spray can that fills all the cavities as it expands, stabilising the sensitive component.	**>PUR<**	Mattresses, cushions, upholstery, roof insulation, wood-lookalike furniture, castings to replicate artefacts and statues, moulds for paving, wall panels, and other concrete castings, adhesives and glues, insulation for fridges, freezers, and cold rooms, and self-skinning foams for automotive components like headrests, dashboards, and steering wheels.
SAN Styrene acrylonitrile	07 SAN	Upmarket cosmetic jars, lip-gloss containers.	**>SAN<**	Printer and other electronic housing components, especially clear sections, mixing bowls and basins for domestic utensils, measuring jugs, water, and juice pitchers.
TPU Polyurethane		*Not generally used as packaging material.*	**>TPU<**	Footwear, hoses, mining screens, automotive components, roller blade wheels, strong and durable footwear, shoe soles, and solid tyres for forklifts and bicycles.

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[6] There are various multilayer materials available, and it is not possible to list all of them here. The principles remain the same: If the packaging is not made with a single material as per polymers 1 to 6, a number 7 is used with the appropriate material acronym(s) underneath.

1.4.

A brief introduction to polymer chemistry

Polymers are used in many aspects of our lives. They have applications in rubbers, textiles, adhesives, explosives, and plastics as we know them today (Figure 1.4; see also Box 1.1). Not included in this list are the natural polymers like keratin and DNA, for example. Plastics are just one category within the broader polymer group.

Plastics are broadly categorised into two subsets, namely thermoplastics and thermosetting plastics (thermosets), each including several different plastic polymers, which determine each type of plastic's technological and physical behaviour. This section delves deeper into the fascinating chemistry of plastic polymers.

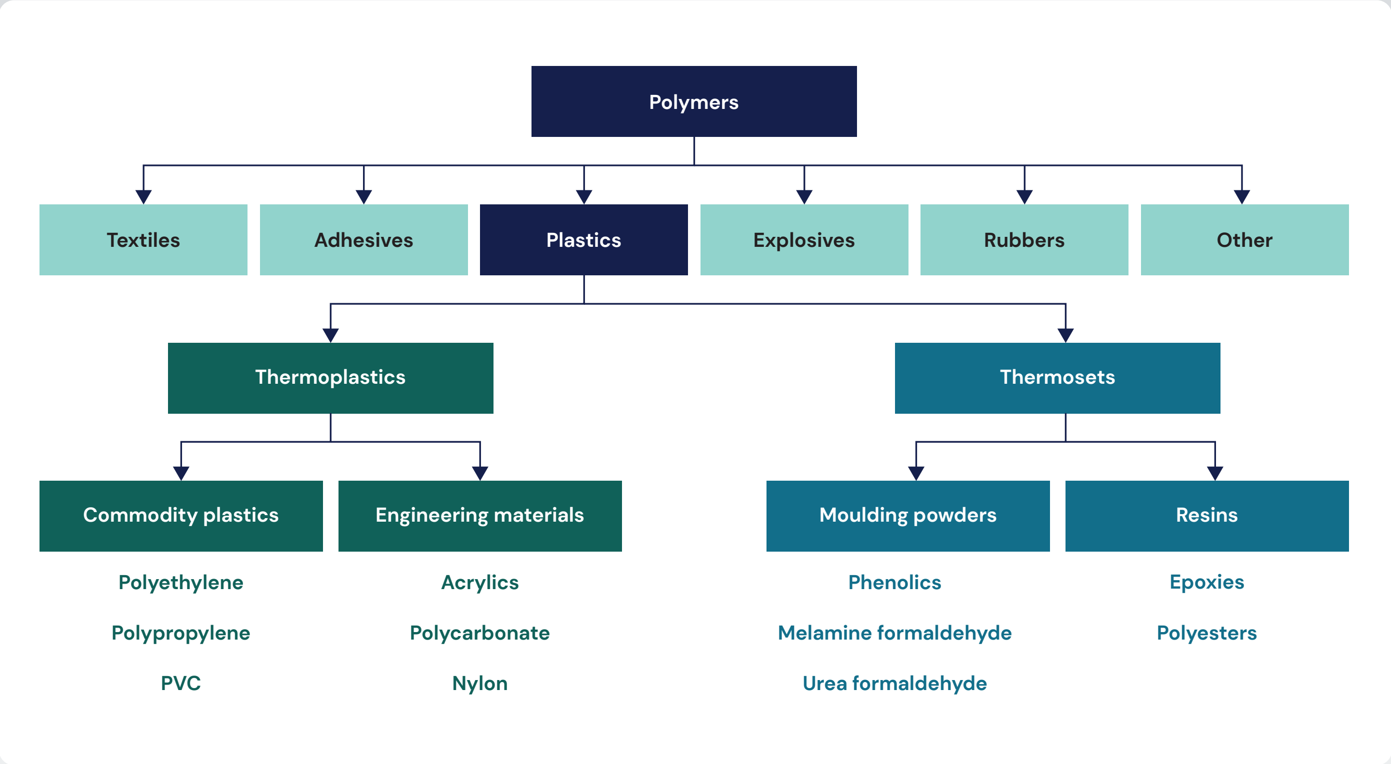


Figure 1.4: *Plastic categories within the polymer group.*

1.4.1. BUILDING BLOCKS: MONOMERS AND POLYMERS

We said earlier that plastics comprise long chains of monomers linked together to form polymers. A monomer is a molecule of atoms (elements) held together by molecular forces. Most monomers are derived from petrochemicals, such as crude oil, coal, and natural gas. However, some are derived from renewable sources (i.e., plant-based sources), such as sugarcane, potato, corn, and agricultural by-products. Examples of plastic monomers include ethylene, propylene, styrene, and vinyl chloride. The simplest monomer is ethylene. It consists of two carbon atoms (C) and four hydrogen atoms (H), with the carbon atoms sharing a double bond. All plastic monomers have this carbon backbone to which other atoms are bound because they are organic molecules. Under suitable conditions, these monomers are joined together to form macromolecules or polymers, usually in a linear shape.

The process of joining monomers together is called polymerisation. We can visualise a polymer with the help of paper clips (Figure 1.5). Suppose many paper clips are strung together to form a chain, then each paper clip represents a monomer, and the chain is the polymer. When only one type of monomer has been used in the polymerisation process, the resultant polymer is called a homopolymer.

It is also possible to combine – or *copolymerise* – two or three different monomers in one polymer chain. These products are known as copolymers and terpolymers, respectively (we'll revisit copolymers later). The name of the monomer, e.g., ethylene, gives its name to the polymer, i.e., polyethylene. An extensive range of polymers can be produced by using different monomers.

BOX 1.1

Is rubber a plastic?

Rubber is a polymer, but is it a plastic too?

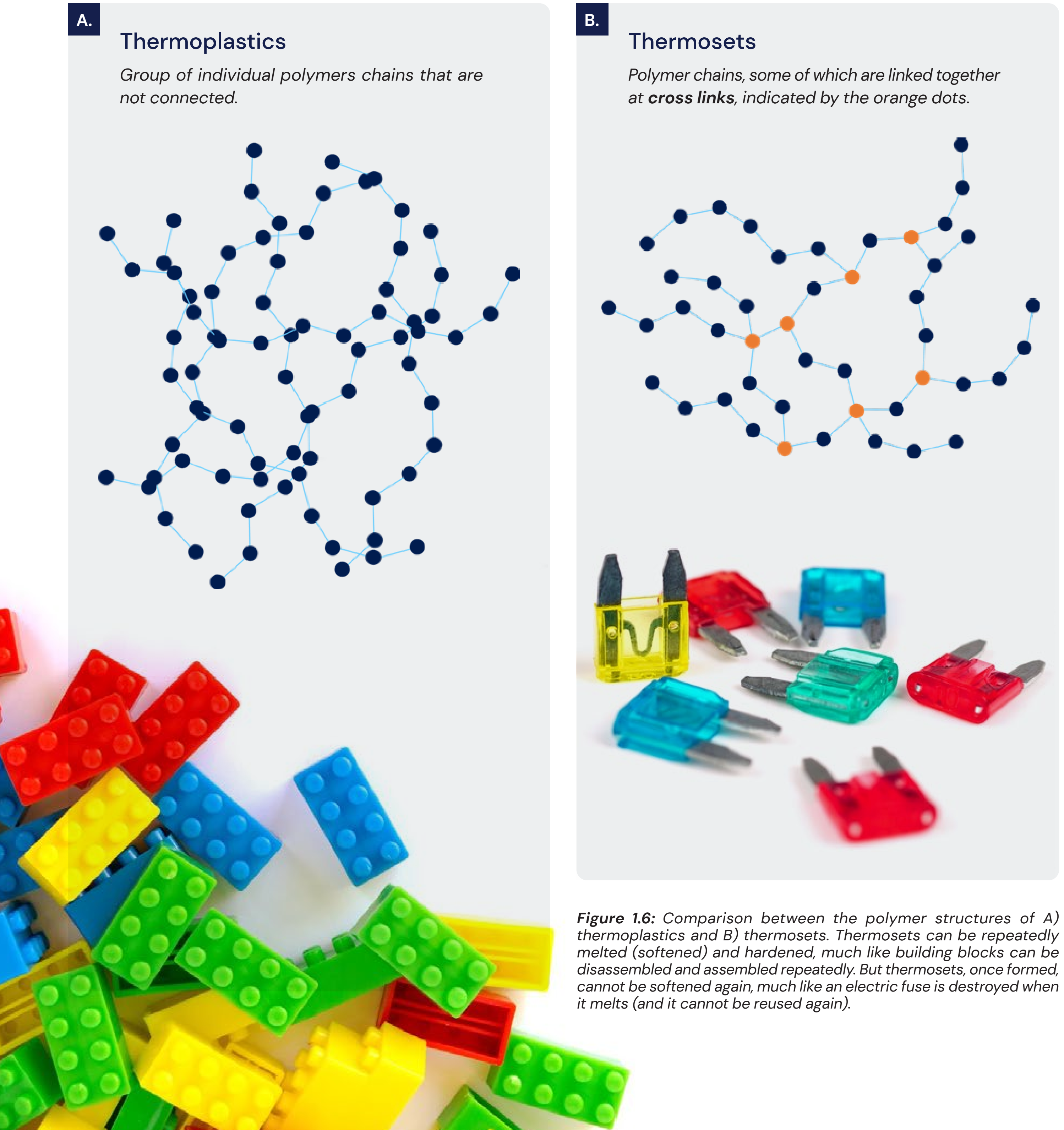
Synthetic rubber, *styrene butadiene rubber* used to make vehicle tyres, is a copy of natural rubber molecules. Over time, as the rubbers were modified to enhance specific properties, many new types of rubber were created. If we only consider the chemistry, they should be considered plastics: They are organic, synthetic, high molecular mass polymers. Although rubber is sometimes lumped with plastics, the general convention is not to include it as a plastic, perhaps because it was always meant to be a copy of the natural product.

Figure 1.5: *A "polymer of paper clips". In this schematic representation, each paper clip represents a monomer; strung together, they form a polymer.*

Plastic products are manufactured from polymers. Bundles of the long chains form one granule of plastic. If we heat the granule, the chains – the individual polymers - shake loose and start to move away from each other. The solid material starts to soften and will flow when soft enough. The softened material can then be moulded into different shapes. Once shaped, the molten plastic is cooled down, and the polymers stop moving, solidifying into a specific shape.

In thermoplastics, polymers stay in their new positions after manufacture until heat is applied, when they will melt again. A thermoplastic can be repeatedly softened by heating and hardened by cooling (Figure 1.6A).

This is like building with blocks, breaking them down, and then building something new with them repeatedly. Conversely, thermosetting plastics do not soften again once formed when heat is reapplied and hence cannot be reprocessed or welded (Figure 1.6B). In thermosets, the molecular chains are chemically cross-linked into much larger molecules during processing (Figure 1.6B). Therefore, these plastics are generally not recycled (but there are the odd exceptions – see García et al. 2014).



A. Thermoplastics

Group of individual polymers chains that are not connected.

B. Thermosets

Polymer chains, some of which are linked together at ***cross links****, indicated by the orange dots.*

Figure 1.6: *Comparison between the polymer structures of A) thermoplastics and B) thermosets. Thermosets can be repeatedly melted (softened) and hardened, much like building blocks can be disassembled and assembled repeatedly. But thermosets, once formed, cannot be softened again, much like an electric fuse is destroyed when it melts (and it cannot be reused again).*

1.4.2. A DEEPER DIVE INTO (THERMOPLASTIC) POLYMER PROPERTIES

Plastics are versatile. Not only are there 45 different types, each with its own characteristics, but each of these polymer types can be used to produce particular products. For example, low-density polyethylene (PE-LD) polymers are used to manufacture bread bags and canoes. How is this possible?

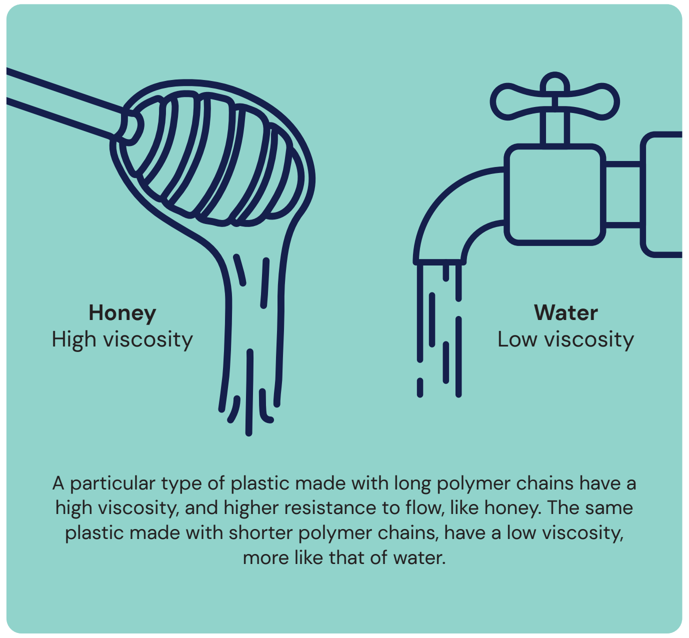
The type of polymer is determined by its chemical makeup, in other words, which atoms (elements) are bound together in a particular order. However, individual polymers of the same type may vary from each other in terms of their molecular chain length, molecular structure, and how these molecules are arranged relative to one another, which will affect the physical and aesthetic properties of that material.

Below, we explore some of these molecular aspects. Additives also contribute to the properties and behaviour of plastic; these are discussed in Section 1.4.3. Here, we will focus primarily on pure thermoplastics.

A. Chain length

Polymerisation produces polymers of different chain lengths; in other words, polymers have different numbers of monomers linked together. Chain length can be measured - or estimated – in terms of a polymer's resistance to flow. Resistance to flow is expressed as the *melt flow index* (MFI). A low MFI indicates polymers with long molecular chains (and a high molecular weight). Different grades of the same material are differentiated by their MFI values. While these grades are still the same polymer, differences in chain length affect properties such as their melt viscosity.

Melt viscosity refers to how easily polymer chains move at a given temperature (Figure 1.7). Polymer chains *move*, for example, when heated and melted during the manufacture of plastic products. Materials with long polymer chains have a high molecular weight and melt viscosity. Their melt will be thick and flow more slowly, making these materials more difficult to process. On the other hand, long molecular chain lengths enhance polymers' mechanical and thermal properties. In simpler terms, their products are stronger and able to withstand higher temperatures without losing their strength compared to those made from short polymer chains. Consequently, by manipulating the chain length of a particular polymer type, products with specific applications and durability can be produced.



A particular type of plastic made with long polymer chains have a high viscosity, and higher resistance to flow, like honey. The same plastic made with shorter polymer chains, have a low viscosity, more like that of water.

Figure 1.7: *The difference between low and high-viscosity materials.*

Polymers of varying chain lengths must be processed differently. Those of shorter chains, or easy-flowing grades, are used in injection moulding, while materials with long polymer chains with higher flow resistance are used for extrusion and blow moulding.

Considering the example of PE-LD polymers, refuse bags are produced using film extrusion moulding, which requires low-flowing grades, while water tanks are manufactured with easy-flowing grades in rotational moulding (see **Chapter 2: *Plastics from raw material to end-of-life*** for more on the manufacture processes of plastic).

B. Molecular arrangements

You may have noticed that some, but not all, plastics are transparent. The translucency of a plastic can be explained in part by the arrangement of its molecular chains, in other words, how these molecules are aligned or ordered relative to each other. The molecular arrangement of thermoplastics can be described as amorphous or semicrystalline (Figure 1.8).

In amorphous thermoplastics, polymers are loosely arranged, like a "ball of cotton wool". This molecular arrangement allows light to pass through the plastic, resulting in a transparent material when unpigmented (Figure 1.8A). Examples of amorphous thermoplastics are polystyrene (PS), poly(vinyl chloride)[7] (PVC), polycarbonate (PC), and acrylic (PMMA).

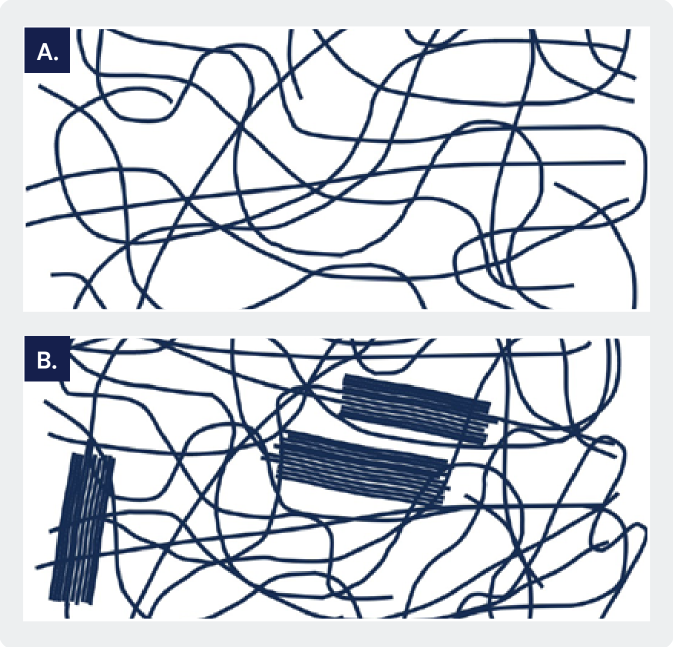


Figure 1.8: A) Amorphous and B) semicrystalline arrangements of thermoplastic polymers.

Semicrystalline (also referred to as crystalline) plastics are characterised by bundles of tightly packed, parallel molecular chains (Figure 1.8B). These bundles are called crystallites, and they prevent light from readily passing through the plastic; they refract or "deflect" the light – leaving these plastics naturally tinted white in their unpigmented form. Crystalline materials tend to shrink more during the cooling stage of manufacturing, which affects the final product dimensions. For example, two bottles made from PVC and PP in the same mould will have different sizes; the PP bottle will be smaller due to higher shrinkage levels of the crystalline PP. The tighter molecular structure of crystalline plastics can also be beneficial by providing better barrier properties to gases, moisture, and light than amorphous materials, making these good packaging options for specific food items. Examples of crystalline materials include polyethylene (PE), polypropylene (PP), acetal (POM), poly(ethylene terephthalate) (PET) (see Box 1.2), and nylon (PA).

BOX 1.2

Clear PET bottles ?

Since PET is a crystalline material, why are cooldrink bottles clear and not opaque?

The manufacturing process for PET bottles is a two-step process. The smaller preform is injection moulded, after which the preform is inflated inside a mould to become a bottle[8]. The preform is cooled rapidly, and the molecules stay amorphous to allow for the expansion process to follow. Once blown/expanded, the molecules are rapidly cooled down and do not have time to crystallise or pack into closer, denser patterns. This results in a clear bottle with a high impact strength.

We can see the crystalline nature of PET with a simple test by heating a portion of a PET bottle with a strong heat source like a hairdryer and letting it cool down by itself. The heated section shrinks, becoming white because the molecules have time to contract into denser sections and crystallise.

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7 There are rules for how to write the names of molecules. According to these rules, monomers must be written in parentheses under certain conditions, to avoid ambiguity. For example, when the monomer name consists of two words, as in the case of vinyl chloride, it must be parenthesized in the polymer name, poly(vinyl chloride).

8 See Chapter 2: *Plastics from raw material to end-of-life* to learn more about how plastics are manufactured

C. Molecular orientation

The strength of plastic is impacted during processing. When manufactured, the polymers line up or orientate in the direction of flow of the molten plastic (Figure 1.9). The mechanical properties of the plastic, such as strength, are different when measured in and across the direction of melt flow. Orientation in the direction of flow increases the tensile strength of a product in that direction.

The direction of polymer orientation can be manipulated during the manufacture of plastics to render specific mechanical properties, depending on the application of a product. The product is stretched up to eight times its original length during processing to achieve the high-tensile properties required for monofilament or strapping tapes. This is called *unidirectional orientation* and is used to produce polypropylene (PP) tapes for woven bags (Figure 1.9A), nylon (PA) monofilament for fishing line or PP hair extensions.

Biaxial orientation (Figure 1.9B) is achieved by stretching the soft heated material in both the direction of flow and the transverse (across-flow) direction. The cross-molecular pattern obtained results in films with excellent puncture strength, improved barrier properties, especially for oxygen, and high transparency. Examples include biaxially orientated PP (BOPP) for wrapping confectionaries, gifts, flowers, or sweets (Figure 1.9B).

Strong orientation can sometimes be unfavourable. As soon as the product is exposed to higher temperatures, the molecules return to a position of less stress, and the product shrinks or warps. This can be seen when an ice cream container lid is exposed to hot water whilst doing the dishes; the once smooth lid becomes warped and twisted.

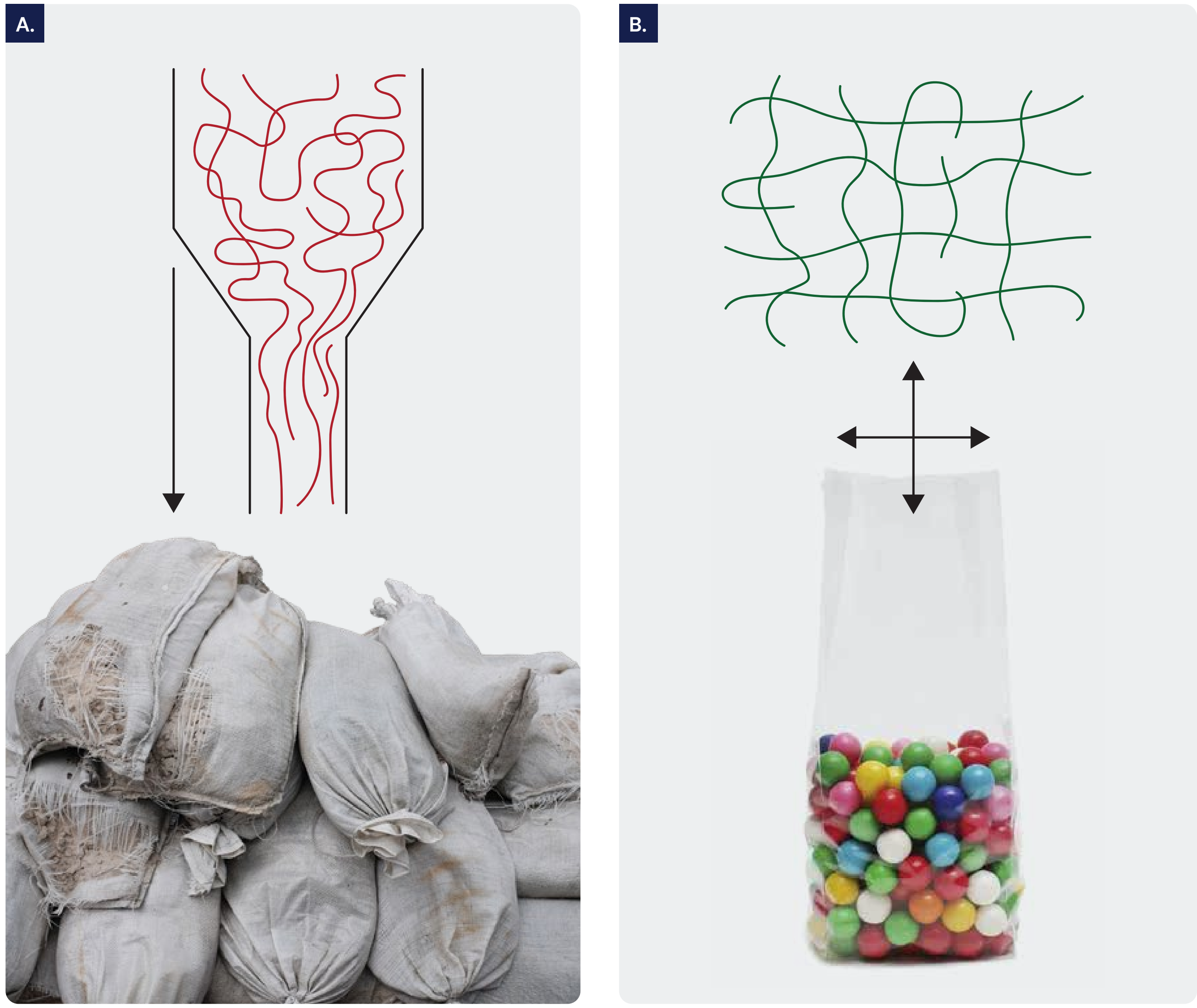


Figure 1.9: *Changing the molecular orientation of a specific type of polymer can enable different applications. A) A unidirectional orientation of PP is used to produce strong materials, such as tapes and bags that can carry sand. B) Biaxial orientation of PP-produced transparent films. (The arrows indicate the direction of polymer orientation.)*

1.4.3. POLYMER MODIFICATION

Most plastics cannot be processed or used in their original form but require the addition of processing aids and additives. The various types of polymers behave differently when exposed to high temperatures and pressures during the manufacture of plastic products. Processing aids, and sometimes reinforcing agents, are therefore added in small amounts to make manufacturing easier or to overcome particular challenges with processing. Plastic products may require specific qualities not inherent to the chosen polymer type for a particular application, in which case additives can be added to achieve the desired characteristics. Additives may be mixed with polymers to produce thermal stability so that they don't distort, melt, or become brittle at a specific temperature range to create a specific colour or a specified softness. Flame retardancy, anti-static properties, and foams also require special additives. While plastic polymers are normally large molecules, chemically inert (they do not react with other chemicals), and without taste or smell, additives, on the other hand, can be organic or inorganic chemicals, sometimes also polymers, which could considerably alter the properties of a plastic. The choice of additives and processing aids is therefore critically important.

It is often impossible to achieve all the desired properties for a product by adding multiple additives since some enhancements may counteract the existing desirable properties of a polymer. Instead, only the most important properties of a specific application must be selected. When choosing additives and processing aids, several criteria must be considered to ensure that they do not negatively affect the properties of the polymer or the final plastic product. Ideally, additives and processing aids should have the following qualities:

- Good light stability to prevent deterioration when exposed to sunlight, i.e., ultraviolet (UV) light;
- Neutral smell and taste;
- Low volatility, i.e., they should remain inside the polymer matrix[9] during processing;
- Resistance to migration, in other words, the additives should remain inside the polymer matrix throughout the life of the plastic product and not leach from it;
- Physiological acceptance, meaning they should not have any harmful impact on human health with continual use and;
- Compatibility with other additives.

There are many different types of additives. Here, we separated them into two groups: protective and modifying additives[10].

A. Protective additives

Protective additives assist with polymer processing, reducing their tendency to degrade, mainly during processing.

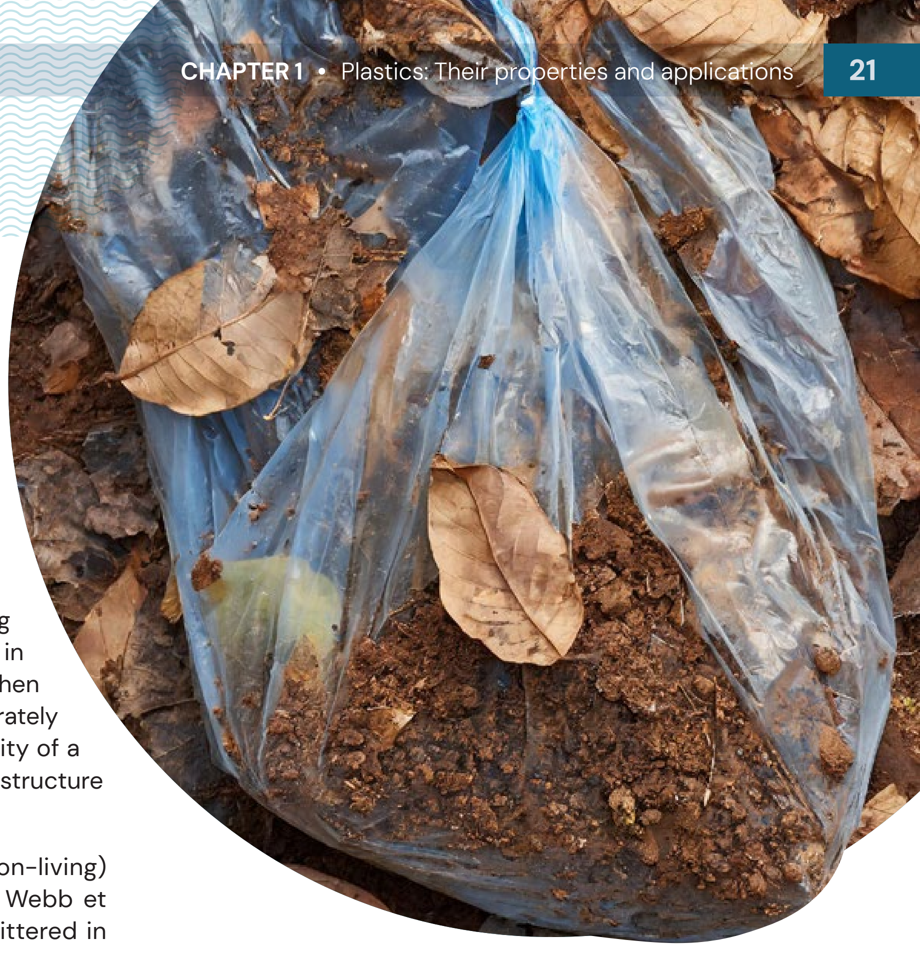
- ***Stabilisers*** protect plastics against heat, UV light, oxygen, and moisture damage. These forces break down the molecular chain, decreasing the polymer's mechanical properties.
- ***Antioxidants*** protect against oxidation. Stabilisers and antioxidants are often added together to slow down degradation.
- ***UV absorbers*** absorb UV rays to slow down photodegradation.
- ***Lubricants*** decrease the internal and external friction in plastic melts.

B. Modifying Additives

Modifying additives are used to change the final properties of the polymer.

- ***Plasticisers*** penetrate between the polymer chains and counteract the intermolecular forces to make the material softer and more flexible.
- ***Extenders*** are secondary plasticisers that are used together with plasticisers to reduce the cost of plasticised compounds. They are considerably cheaper than plasticisers and also improve processability.
- ***Colouring** agents* soluble (dyes) or insoluble (pigments) materials used to add colour to a plastic.
- ***Fillers*** are used to change the density and volume of plastics to cut costs and obtain specific properties. For example, calcium carbonate can be used in plasticised PVC to provide a dry grip or increase density.
- ***Anti-static*** agents rreduce or prevent the build-up of static electricity. The anti-static agents conduct static charges formed by friction by migrating to the material's surface and attracting moisture from the air. This moisture film prevents static charges from accumulating on the plastic.
- ***Foaming*** or ***blowing*** agents form gases at specific temperatures to obtain a cellular structure within the polymer in a liquid or molten state. The foam structure is retained when the melt solidifies, as in the case of expandable polystyrene. Chemical foaming agents decompose at specific temperatures to form gases such as carbon dioxide (CO_2) or nitrogen (N_2).
- Different ***flame retardants*** are used to resist burning by:
  - › Excluding oxygen from the flame;
  - › Changing the decomposition pattern of the plastic;
  - › Changing the burning mechanism or by;
  - › Making the plastic difficult to ignite.

1.4.3. DEGRADATION



We cannot discuss plastics, their applications, and durability without discussing *degradation*. Degradation refers to the breakdown of a material. In the context of plastics, the degradation process causes long polymer chains to break, which results in the loss of important physical properties such as impact strength, tensile strength, or colour. Molecular chains break when these polymers are exposed to one or more environmental factors, such as heat and light, chemicals, or due to mechanical degradation. The resulting changes may be undesirable, such as changes occurring during product use. Degradation may also be desirable, as in the case of biodegradation or during processing when the molecular weight of a polymer is lowered deliberately to change its chemical properties. The susceptibility of a polymer to degradation depends on its molecular structure (Speight 2019).

Plastics can degrade through several abiotic (non-living) and biological (biotic) processes (Andrady 2011, Webb et al. 2013) during their manufacture, use, or when littered in the environment:

- ***Photodegradation*** refers to the combined action of sunlight and air and can be observed as cracking, chalking, and colour changes. Plastic litter in cold, dark places such as the bottom of the ocean or under layers of soil in a landfill, on the other hand, may remain intact for quite long.
- ***Thermal degradation*** occurs during processing at temperatures higher than the melting points when the polymer is transformed from solid to melt. Discolouration (brown spots or black specks) is often due to thermal degradation.
- ***Chemical degradation*** occurs when plastic is in contact with an incompatible chemical. The chemical attacks the plastic, breaking down the polymer structure. An example would be the blistering of a vinyl shower curtain or tablecloth when nail polish remover is spilt on it.
- ***Mechanical degradation*** occurs during processing when the polymer is subjected to powerful shearing forces. Plastics can also suffer from mechanical degradation during use through grinding, shearing, or repeated bending and flexing. Plastics may also break down mechanically in nature, for example, when plastic litter is exposed to strong wave action on rocks.
- ***Biodegradation*** happens when a material is broken down into simpler constituents by microorganisms, mainly aerobic (air-breathing) bacteria, into natural substances such as carbon dioxide, water, ammonia in some instances, and mineral components if present initially. Biodegradation can also be anaerobic (in the absence of oxygen), in which case methane is another end-product of decomposition (see Section 1.6.2. for more about biodegradation of "bioplastics").

Theoretically, conventional (petrochemical) plastics can biodegrade (Webb et al. 2013). In fact, scientists have discovered 246 strains of bacteria - often from landfills or dumpsites - that can digest plastics (Matjašič et al. 2021). Crucially, this does not mean that conditions are always favourable for bacteria to decompose plastics.

The biodegradation of plastics in the environment is slow because it is difficult for most bacteria and other microorganisms, such as fungi, to break their strong molecular bonds. Microorganisms generally require plastics to break down into smaller pieces through abiotic processes before they can "attack" the plastic. Furthermore, adding stabilisers to slow down the undesirable degradation of plastics while in use increases the durability of plastic products but also makes naturally occurring biodegradation even more difficult. Therefore, conventional plastics – those not certified as biodegradable or compostable – are generally considered non-biodegradable.

Some scientists have pointed out that we still have much to learn about the abiotic and biotic degradation of plastics in nature. Plastics are often reported in the media to have lifetimes of many decades to thousands of years or even "forever". However, scientific research has not validated many of these estimates; some are gross overestimates (Ward and Reddy 2020). Still, most plastic litter persists for at least several years in the environment and, depending on the plastic type and the environmental conditions to which they are exposed, some likely last for a significantly longer time (Chamas et al. 2020), where they can cause damage as pollution. We, as consumers, must use and dispose of plastic goods wisely and responsibly.

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[9] The polymer matrix refers to the polymers that make up a particular plastic. Additives can be added to this matrix. If we use a biscuit analogy, the polymer matrix would be the dough into which the choc-chips or nuts (the additives) are blended. The choc-chips and nuts do not really become part of the dough, but they give the final product its distinct taste and aesthetics.

[10] Chapter 2: *Plastics from raw material to end-of-life* looks at the way plastic material is prepared, and additives added, for use by the converter.

1.5.

Types of plastics

We saw earlier that plastics are divided into thermoplastics and thermosets. One of the main differences is that thermoplastics melt when heat is applied, whereas thermosets do not melt when reheated. Thermoplastics are further subdivided into commodity and engineering plastics. Commodity plastics are pervasive and can be used in just about all market sectors, particularly as packaging materials. Engineering plastics are developed and selected for targeted applications where one or more characteristics – e.g., its superior heat resistance or better creep and abrasion resistance – make it ideal. Each of these groups includes a wide variety of plastics.

Thermoplastics form the largest group of polymers. The period since the mid-1960s has seen the growth of applications for technical and temperature-resistant plastics in fields previously dominated by metals. Despite higher production costs than metals used for similar purposes, their use has been justified for technical applications. Further advances have resulted in the introduction of elastomers and alloys, while the development of biologically degradable thermoplastics is currently receiving much attention. Today, the most-used plastics are polyolefins, polystyrenes, and polyvinyl chlorides (Geyer et al. 2017), which are thermoplastics. Together, these represent more than two-thirds of the total amount of plastics produced worldwide. Of these, the polyolefins can be considered the most important group of polymers in terms of tonnage. Polyolefins are a family of polyethylene and polypropylene plastics where the molecular chains consist of only hydrogen and carbon atoms. Their versatility has made them extremely popular.

As discussed, thermoplastics used for packaging applications have a specific identification code. Commodity plastics are allocated with a number from 1 to 6 when used as packaging to indicate a specific polymer. The number 7, however, indicates 1) materials used in packaging that are not polymer numbers 1 to 6 (hence “other”) or 2) some combination of plastic types rather than a single polymer.

These combinations can be a blend between polymer numbers 1 to 6, such as high-density polyethylene (PE-HD) and low-density polyethylene (PE-LD), polymer numbers 2 and 4, respectively, used for milk bottle caps, or multilayered structures made by combining different types of thermoplastics to achieve specialised and unique characteristics. As an example of the latter, processed meat packaging requires an effective oxygen and moisture barrier as well as clear packaging to make the contents visible, which can be achieved by combining polyethylene (PE), poly(ethylene terephthalate) (PET) and/or nylon (PA).

This section describes the properties, applications, and identifying characteristics of the dominant plastics in use today, including some “bioplastics”. Detailed descriptions of the processing methods of the different types of plastic are provided elsewhere. This is not a complete discussion of all 40+ synthetic plastics currently used. This section serves only as an introduction to the more common types of plastics. Although abundant, synthetic textiles are also not discussed in detail here (and the polymer properties described in the following subsections may not apply to the fibres of that type of plastic). A simple identification key to distinguish among the different types of thermoplastic and thermosetting plastics (Table 1.3) is provided at the end of this section. Plastics give us clues about their “identity”, which do not require a degree in chemistry to interpret. It is possible to distinguish between some of the more commonly used plastic polymers by investigating whether a plastic object floats in fresh water and seawater, how it burns, whether it is possible to scratch its surface with one’s fingernail, and even what sound they make when dropped.

> **If you plan on burning plastics for testing, only use small pieces in a well-ventilated area with no risk of a fire spreading, and be careful not to inhale any fumes.**

1.5.1. POLYETHYLENE (PE-HD, PE-LD, PE-LLD)

Polyethylene is one of the most common types of plastics in use today. Grocery/carrier plastic bags and plastic wrapping are the most common applications of polyethylene. By varying the way ethylene monomers are polymerised, different types – or grades – of polyethylene can be created. The most important grades, in terms of volumes sold, are high-density polyethylene (PE-HD), low-density polyethylene (PE-LD), and linear low-density polyethylene (PE-LLD). These grades are distinguished by the density and branching of their polymers (Figure 1.10), crystal structure, and molecular weight, which result in unique characteristics for each.

A. Types and properties

High-density Polyethylene (PE-HD)
PE-HD (also abbreviated HDPE) has minimal branching (Figure 1.10A), giving it the highest degree of crystallinity among the polyethylenes. This is the hardest and stiffest polyethylene and will never be clear (transparent). It is commonly used for bottles and drums for food, non-food materials, and chemicals. As a film, the higher degree of crystallinity gives it better tensile strength and handled carrier bags made from PE-HD can be thin *and* strong. Even when carrying a load of shopping, the bags will not stretch.

Low-density Polyethylene (PE-LD)
PE-LD (also abbreviated as LDPE) is a highly branched polymer (Figure 1.10B). This prevents the polymers from being packed in tight, orderly crystalline patterns, giving PE-LD the lowest degree of crystallinity of all polyethylenes. As a result, PE-LD is softer and clearer than the other grades.

Linear low-density Polyethylene (PE-LLD)
PE-LLD is characterised by orderly molecular chains with consistent and even branching (Figure 1.10C). The degree of crystallinity is higher than for PE-LD and less than for PE-HD. Although mostly linear, molecular chains are not easily separated, and films made from PE-LLD have exceptionally high puncture resistance, even when stretched. This characteristic makes it an ideal material for clear, thin pallet wrap or clear, thin, sticky wrap used in the kitchen.

Special types of polyethylene
Other types of specialised PE include ultrahigh molecular mass, cross-linked, and chlorinated polyethylene. Ultrahigh molecular mass polyethylene is used for high-wear engineering applications, like conveyor systems in bottling plants. Conventional processing is not possible due to the material’s difficult flow. Cross-linked polyethylene is used for high-service temperature applications for hot-water pipes and underfloor heating cables where the intermolecular bonds prevent premature softening of the material when used consistently at higher temperatures. Chlorinated polyethylene on its own serves little purpose. Still, it has several applications in blends with PVC to improve the impact strength of PVC, especially in cold conditions (PVC is discussed in more detail in Section 1.5.4.).

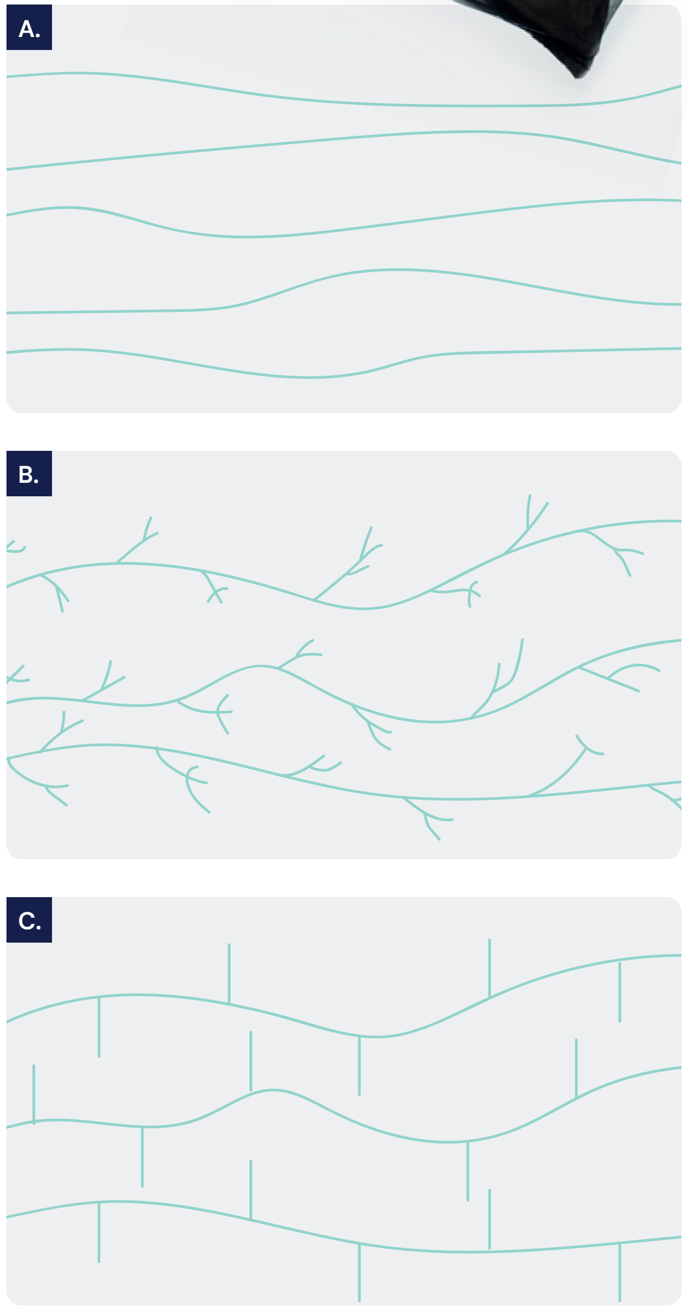


Figure 1.10: *Polymer branching of different grades of polyethylene: A) high-density, B) low-density, and C) linear low-density polyethylene.*

Despite having their unique features, the various grades of polyethylene grades also share several common characteristics:

- Low specific gravity: All grades of polyethylene float on water;
- High toughness and tensile strength. Consider, for example, how many groceries can be carried in a thin plastic shopping bag;
- Resistance to temperatures from -50°C to 90°C. Of the different polyethylene grades, PE-HD can withstand the most extreme temperatures;
- Milky white translucency if unpigmented;
- Good electrical insulation, as can be seen in telecommunication cables;
- Low water absorption;
- Much greater permeability to oxygen and water vapour, odour, and aromatic agents than most other polymers;
- UV exposure causes brittleness and;
- Chemical resistance increases with an increase in density. PE-HD is particularly useful for chemical storage containers.

Small variations in density have a considerable effect on polymer properties. A *lower-density* polyethylene, given constant melt flow properties (molecular mass), exhibits:

- A lower softening point (melts at lower temperatures than higher-density polyethylene);
- Greater flexibility;
- Lower tensile strength;
- Greater gas permeability;
- Greater transparency;
- A less glossy appearance and
- Lower chemical resistance.

To conclude, PE-HD has a higher density than PE-LD and, therefore, a higher softening point (it requires a higher temperature to become soft), greater chemical resistance, and is glossier than PE-LD.

B. Applications

PE-LD and PE-LLD

The major attributes of PE-LD are ease of processing, relatively low production costs, and good water resistance. The major markets for PE-LD are films for food and non-food packaging, construction, and agricultural products. PE-LD is also used to produce low-pressure pipes for cold water applications such as irrigation. Its excellent electrical properties make PE-LD useful for cable insulation in telecommunications and high-frequency signal cables in electronic equipment. Coated and laminated films use PE-LD as a heat-sealing and adhesion layer between dissimilar materials. PE-LD is also used in the sinter coating of wire racks and trays. PE-LLD is used in rotationally moulded products like water tanks, sewage tanks, animal feeding troughs, pontoons, kayaks, and more (see Figure 1.11).

PE-HD

Bottles and jars from PE-HD are used for dairy products, fruit juices, personal- and domestic care, chemicals, lubricants, foodstuff, and non-food fluids. PE-HD is used to produce shopping/carrier bags, refuse bags, and food packaging films requiring high tensile strength and slightly better oxygen barriers. Stretched tapes are used for knitted shade cloths and agricultural netting for crop protection or shade (see Figure 1.11). High-pressure pipes for water reticulation or wastewater are made from PE-HD. PE-HD is also used to produce injection moulded products ranging from high-volume caps and closures for beverages to large industrial mouldings and packaging crates suited for cold storage.

C. Identification of polyethylene

Polyethylenes:

- When polyethylene products are dropped onto a hard surface, they make a dull noise;
- Polyethylene is less dense than freshwater and seawater; its products, therefore, float on water (the density of clean freshwater is 1.00 g/cm^3, and 1.03 g/cm^3 of seawater);
- Polyethylene products feel like candle wax;
- Polyethylene burns with a yellow flame dripping molten material. The smoke generated smells like candle wax and;
- A fingernail easily marks the surface of polyethylene products. The higher the density, the harder it is to mark the surface (this characteristic helps to distinguish between PE-LD and denser PE-HD).

Figure 1.11. *Examples of polyethylene products.*

1.5.2. POLYPROPYLENE (PP)

Polypropylene is a semicrystalline polymer with a tighter, more orderly arrangement of molecular chains, giving it higher thermal stability and better barrier properties than polyethylenes. It is available as homopolymers (propylene monomers only) or copolymers (propylene and ethylene monomers). Polypropylene can be used for a wide variety of rigid products, e.g., garden furniture, storage containers, and car bumpers. PP can also be manufactured into thin, crisp, clear films or metallised to look like aluminium foil. PP films are used to wrap sweets, confectionery, stationery, or clothes.

A. Properties

Typical properties of polypropylene are:

- Low density (PP items float in water);
- High stiffness,
- Hardness and strength. PP objects have a high strength-to-weight ratio, i.e., they are surprisingly strong for their mass;
- Temperature resistance up to 110°C;
- Milky white translucency if unpigmented (not dyed). Clear (high transparency) when biaxially orientated and;
- Resistant to weak inorganic acids, alkalis, alcohol, and some oils and washing soda at temperatures up to 100°C.

B. Applications

Their ease of processing, higher service temperatures, excellent strength-to-weight ratio, chemical resistance, and surface hardness make PP extremely useful in consumer product packaging and the engineering industry. As expected, the range of PP applications is extensive (Figure 1.12).

PP film is a popular packaging material for fresh produce and non-food products because of its clarity. Orientated films (see Section 1.4.2.C.) can remain clear or can be metallised for packaging, especially to wrap snacks and confectionaries. In contrast, orientated tapes and monofilaments are used for ropes, woven tarpaulins, woven bags, strapping, artificial grass, hair extensions, and carpeting. PP is also used to produce bottles for personal and domestic care products, caps and closures, and integral hinged containers or closures such as those used on shampoo bottles. Larger applications of PP include crates and bins, chairs and furniture components, automotive components, and thin wall packaging for dairy products.

C. Identification

As a polyolefin, PP shares specific characteristics with polyethylene. It is still possible to distinguish PP from the latter and other types of plastics:

- PP has the lowest density of all the major thermoplastics and hence floats on water;
- PP is harder and stiffer than polyethylene; and
- Objects made from PP are more challenging to scratch with a fingernail than PE-HD.

A burn test reveals several more interesting characteristics of PP (always be careful when conducting a burn test):

- If PP does not contain a flame retardant, it burns like a candle with a blue flame, forming droplets of molten material (melt) with little smoke.
- The generated smoke smells like kerosene or paraffin.
- When a cold rod or pencil is used to hook the melt, it is easy to draw fibres.

Figure 1.12. *Examples of polypropylene products.*

1.5.3. STYRENE-BASED POLYMERS (PS)

The following materials are all derived from the styrene monomer. The three main groups of styrene polymers typically used in the plastics industry are solid polystyrene, expandable polystyrene, and styrene copolymers. These groups and their properties are described below.

A. Types and properties

Solid Polystyrene

Solid polystyrenes range from crystal general-purpose polystyrene with high rigidity and gloss to toughened high-impact polystyrene (PS-HI), which is opaque and less glossy. Thick crystal polystyrene sheeting is used for shower doors or fridge liners. Thinner sheeting is used for take-away containers or yoghurt cups. Clear display boxes for souvenirs or chocolates are also made from solid polystyrene.

Solid polystyrene, and in particular crystal polystyrene, can be described as:

- Hard and rigid;
- Brittle, resulting in low impact strength (not the case for PS-HI);
- Transparent with high brilliancy;
- Dimensionally stable. In other words, objects keep their original shape while in use (they have good structural integrity);
- Comparatively easy to process to manufacture products over a wide range of temperatures;
- Resistant to water/have low moisture absorption, even when left immersed in water;
- Chemically inert, meaning it does not react with chemicals;
- Free from odour and taste and;
- Able to remain suspended in clean water, i.e., it does not sink or float, having a density similar to that of the water (this excludes extruder gassed PS).

Toughened high-impact polystyrene (PS-HI) was developed to counter the disadvantage of the low-impact strength of crystal PS. Butadiene rubber (BR) is incorporated into the PS-HI polymer to strengthen it. Toughened polystyrene retains many of the properties characteristic of crystal polystyrene, except for having:

- Higher impact strength;
- Lower transparency (opaquer); and
- Less gloss.

Extruder-gassed PS is produced from crystal PS using a specialised foaming process while making the sheeting. These are used to produce lightweight, low-density trays for meat packaging and takeaway food containers, for example. They should not be confused with expandable PS described below (see also Figure 1.13).

Expandable Polystyrene (PS-E)

Expandable PS comprises tiny beads of polystyrene containing a volatile blowing agent called pentane that will become a gas at high temperatures (Figure 1.13). Heat is applied as steam, and the pentane gas expands the softened beads to 30 or 40 times their original volume to achieve densities as low as 1.2 to 1.4 kg/m^3. To put this into context, an expandable PS block the size of a 6m shipping container would only weigh 40kg. A solid block of PP weighing 40kg will be roughly the size of a large shoebox (35 x 35 x 35cm).

The main properties of PS-E are:

- Lightweight with high rigidity;
- Less dense than water;
- Good cushioning properties make it an excellent protective packaging material;
- Good thermal insulation properties;
- Smooth surface, and;
- Inert to foodstuffs, meaning that the coffee or tomato sauce will not damage or degrade the polystyrene, and it will, therefore, not adversely affect the contents of the cup or container.

Figure 1.13: *Comparison between A) extruder gasses and B) expandable polystyrene. Extruder-gassed polystyrene lacks the tiny beads visible in expandable polystyrene.*

Styrene copolymers and terpolymers

Some polystyrene products are manufactured from styrene copolymers or terpolymers, i.e., their polymers consist of two or three different types of monomers. The major grades of these types of PS are the copolymer styrene acrylonitrile (SAN), which consists of the monomers *styrene* and *acrylonitrile*, and the terpolymer acrylonitrile butadiene styrene (ABS), which includes the monomers *acrylonitrile*, *butadiene*, and *styrene*.

ABS resembles PS-HI but with improved impact strength, chemical resistance, and gloss. ABS is typically used to house electronic devices. SAN, which is used for fancy cosmetic jars, has properties similar to that of crystal grades of polystyrene, although the acrylonitrile results in:

- Marginally better impact strength;
- Improved chemical resistance to oil, fat, and grease; and
- Greater absorption of moisture compared to crystal PS.

Figure 1.14: *Examples of polystyrene products.*

B. Applications

Because polystyrenes are easy to process, a wide range of products exploit their rigid glossy character (Figure 1.14). Crystal polystyrene is moulded into food containers, transparent drinking beakers, tumblers, display boxes, toys, cosmetic jars, and more. Extruder-gassed foamed sheets of crystal PS are used to form meat and fresh produce trays, takeaway food containers, and suspended ceiling boards. PS-HI is used for dairy packaging tubs and stationery items such as pens and rulers. Extruded PS-HI sheets are thermoformed into fridge and freezer linings.

Expandable PS is formed into seed trays, protective packaging, cooler boxes, vending cups, and other products. It is also produced into large sheets used for cold storage insulation, display boards, and ceiling panels.

SAN and ABS are used where their superior properties are required over those of polystyrene homopolymers. SAN is used for oily personal care packaging like lip gloss. ABS is a widely used housing material for computers, laptops, remote controls, etc. Painted or metallised finishes are used for automotive components, bathroom fittings, fashion jewellery or furniture handles and knobs.

C. Identification

To determine if a piece of plastic is PS or some other type, drop the plastic a few centimetres onto a hard surface. A metallic noise indicates a polymer which contains styrene or polycarbonate (polycarbonates are discussed in Section 1.5.6.B. under *Engineering Polymers*). To identify a specific type of PS, burn a small piece of polystyrene, blow out the flame, and smell the resultant smoke (do this in a well-ventilated space):

- Sooty bits in the air resulting from the smoke are a definite sign of styrene.
- The smell of styrene indicates PS or PS-HI.
- A styrene smell, together with a bitter taste, indicates SAN.
- A bitter taste and rubbery smell are indicative of ABS.
- The SAN and ABS mouldings sink in water since their densities are marginally higher than those of water. PS tends to suspend itself in clean water and floats in salty water. PS-E will float as it is more air than material, resulting in a surprisingly low density.

1.5.4. VINYL POLYMERS (PVC)

PVC is made from vinyl chloride monomer—a carcinogenic—and is manufactured using coal (in South Africa) and salt as basic raw materials. Chemists have known PVC since the late 1800s. However, it was much of a curiosity until sometime during World War 2, when it was used to replace rubber insulation on wires and cables. Since the early 1950s, the use and applications of PVC have grown rapidly.

PVC can be modified with plasticisers to obtain products other than the natural, unplasticised, rigid type. In fact, PVC is never manufactured into plastic products in its natural polymer state; additives are always added to PVC before conversion. PVC is classified based on the amount of plasticiser and other components added: Rigid PVC-U is unplasticised. Flexible PVC-P is plasticised. PVC plastisol and PVC organosol contain solvents as well as plasticisers. Here, we will focus on PVC-U and PVC-P.

A. Types and properties

PVC-U

Rigid PVC is a strong, robust polymer and generally has the following properties:

- Great mechanical strength;
- It is stiff and hard;
- High resistance to environmental stress cracking;
- Good low-temperature impact resistance (they are less likely to become brittle and break in cold conditions);
- Resistant to alkalis, alcohols, fats, petrol, and detergents;
- Good ability to withstand weathering if it is UV stabilised and;
- Self-extinguishing on removal of flame (e.g., when doing a burn test).

PVC-P

Again, the properties of flexible PVC depend significantly on the amount and type of plasticisers added. Compared to PVC-U, PVC-P generally has:

- Controllable and varied flexibility;
- Improved toughness;
- Slightly lower chemical resistance and;
- Poorer weathering properties.

B. Applications

PVC is perhaps the most versatile and diverse type of plastic today (Figure 1.15). Rigid PVC is primarily used in the building and construction industry for pipes, fittings, window and door profiles, gutters, plumbing, cladding, blinds and louvres, ceilings, and fascia boards, as well as laminated flooring and cornices. PVC-U is also used to produce conduit and trunking for electrical and communication cables. Although the packaging market is shrinking, PVC-U is still used for personal care bottles (especially larger integral handled bottles), honey, and pharmaceutical dispensing. Skin and blister packaging is also made from rigid PVC. Tamper-evident sleeving for glass and plastic containers is made from rigid PVC films.

PVC-P is similarly used in the building and construction industry for flooring, curtaining, and patio enclosures. Cable and wire-covering for low-voltage cables, mould-on plugs and extension cords are produced from PVC-P. In the packaging industry, flexible PVC cling wrap is used to wrap fresh produce, meat, and chicken portions. Flexible PVC is used for medical intravenous tubing, erasers, draglines in mines, and wear-resistant flooring. Pouches, suitcases, and more durable bags are made from PVC cloth. Shower curtains, tablecloths, and upholstery materials are some of the domestic applications for PVC-P.

In sports and leisure applications, coated PVC cloth is used for jumping castles, rubber ducks, tarpaulins, tents, and flooring. The transport industry also uses coated PVC cloths. Many of the soft, leather-like finishings inside cars are made of PVC, e.g., the dashboard skin and door panels. Shoes and shoe components, sandals, and footwear generally use high volumes of flexible PVC.

NOTE: The monomer vinyl chloride is a carcinogen (cancer-causing), PVC dust may cause respiratory irritation, and certain PVC additives are toxic. Only use PVC products as intended; do not burn PVC.

C. Identification

From the list of applications, it is apparent that PVC can manifest in many physical forms. PVC may be transparent or opaque, rigid or flexible. A thin, rigid PVC sheet may have a metallic ring when struck, while a thick sheet has a dull, thud-like sound. Flexible PVC can be quite rubbery and elastic. Despite the diversity of PVC, there are some common characteristics distinguishing rigid and plasticised PVC from other plastics.

To test if an object is made of PVC-P or PVC-U, burn a small piece of plastic, blow out the flame, and smell the resultant smoke:

- Rigid PVC will ignite with difficulty when held in a flame and burn with a sooty, yellow flame. The evolved gases are acidic and produce a sharp, unpleasant smell.
- Plasticised PVC may burn quickly (provided no flame retardants are added). The flame is yellow and sooty, and the evolved gases have a sweetish and *sharp, acrid* smell. The flame is self-extinguishing, and the plastic will stop burning when removed from the flame.

The most conclusive way to test for PVC, plasticised or not, is to ignite a small piece of the plastic on a copper wire. If the flame has a distinct greenish tinge, then the sample is PVC. Finally, PVC sinks in water due to its high density, which also helps to distinguish it from many other types of commonly used plastic.

Figure 1.15: *Examples of polyvinyl chloride products.*

1.5.5. POLY(ETHYLENE TEREPHTHALATE) (PET)

PET, sometimes also abbreviated PETP or PETE, is formed by the condensation of *ethylene glycol* with *terephthalic acid* or dimethylene-terephthalate. One of the main applications of PET is cooldrink (soft drink) and water bottles. It is also used for quite thin, clear, high-tenacity films. A significant application of PET is textiles.

PET is a thermoplastic polyester. Polyesters are polymers (natural or synthetic) where ester (CO-O) groups link the monomers together. Other examples of thermoplastic polyesters include polyethylene terephthalate glycol (PETG), polybutylene terephthalate (PBT), and polycarbonate (PC).

A group of thermosets is also categorised as polyesters. Some polyesters occur naturally (i.e., they are not synthetically produced), such as cellulose, chitin, and proteins, and are of biological importance. Strictly speaking, polyesters include several other types of plastic and even natural chemicals, although we typically refer to PET textiles when we talk about "polyester".

PET should not be confused with PETG, a glycol-modified version of PET. PETG is used to manufacture clear bottles due to its chemical resistance and formability for personal and domestic care bottles; PETG filament is also widely popular for 3D printing. Critically, PETG products cannot be recycled with PET and constitute a significant contaminant if deposited in the waste stream earmarked for mechanical recycling.

A. Properties

Biaxial orientation dramatically improves PET's mechanical properties and reduces gas permeability (see Section 1.4.2.C.). PET is used in packaging because of its clarity and gloss. Recycled PET can be used in contact with food, and recycled beverage bottles are, therefore, popular for recycling back into beverage bottles and sheeting for food packaging.

PET packaging material (excluding textiles) has the following properties:

- It is tough, even at low temperatures;
- Has low water absorption;
- Is resistant to water at room temperature, diluted acids, alcohol, oils, fats, and neutral and acidic salts and;
- It is not resistant to alkalis, steam, ketones, phenols, esters, or chlorinated hydrocarbons.

B. Applications

PET is used to produce clear bottles for carbonated drinks, water, energy drinks, and food products (Figure 1.16). PET sheeting is thermoformed into trays, clam shells, and punnets for fresh produce, meat, and dairy products. Due to consumer pressure, PET has replaced PVC in many packaging applications, e.g., clear display packaging, window boxes or blister packaging.

Films are used for video and audio tapes, electrical insulation, and magnetic storage tapes on bank cards. PET films are often used together with polyethylene for oxygen barrier films. PET fibres and tapes are used for technical woven materials — i.e., materials not used in clothing or for domestic purposes — designed to perform a specific function. In addition, artificial lawns, carpeting, and upholstery are made from PET.

C. Identification

PET can be identified through its higher density relative to water and by the way it behaves when burned:

- A small piece of PET will sink in clean water. Note that an air-filled bottle with its lid on is less dense than water and will float.
- Burns with a yellow flame and gives off black smoke.
- It has a sweet, aromatic smell when burnt.
- Whilst burning, the melt bubbles.
- When a cold rod or pencil is used to hook the melt, fibres (similar to PP) are easily drawn.

Figure 1.16: *Examples of polyethylene terephthalate products.*

1.5.6. ENGINEERING POLYMERS

Engineering plastics are a group of materials that have better mechanical and/or thermal properties than the more widely used commodity plastics. Being more expensive, engineering plastics are produced in lower quantities and tend to be used for smaller objects of low-volume applications. In many applications, engineering plastics have gradually replaced traditional materials, such as wood and metal. Besides equalling or surpassing them in weight-to-strength ratio and other properties, engineering plastics are much easier to manufacture, especially in complicated shapes. The more common materials are discussed briefly below.

A. Poly(methyl methacrylate) (PMMA)

PMMA is an amorphous plastic and one of the family of acrylic materials that is best known for its optical properties and ability to withstand weathering. It has a better *light transmittance* than glass, meaning more light passes through PMMA than glass, but it has approximately ten times the strength of glass in impact strength. Colourability is also good. PMMA is used for many outdoor applications because it can withstand UV radiation without any additives, a unique property among plastics. PMMA is also dimensionally stable, meaning it keeps its shape well. Like other amorphous materials, it softens over a wide temperature range, which is useful for thermoforming. PMMA is, however, more brittle than polycarbonate (see below). It is plasticised - softened - by alcohols, dissolved by chlorinated hydrocarbons, and attacked by aromatic hydrocarbons, ketones, and esters. PMMA remains unaffected by water.

Applications

PMMA has many applications due to its excellent mechanical, optical, and weathering properties (Figure 1.17A). Its optical properties are utilised in spectacles, lenses, prism components, projectors, watch glasses, and flexible optical fibres. In the electronic industry, it is used in instrument panels, safety lamps, control knobs, light covers, lighting strips and illuminated street signage. The automotive and transport industry uses PMMA in reflectors, rear lights, warning triangles and traffic lights. Impact-modified sheeting is used as protective glazing at ATMs, railway carriages, glazing for bank counters, aeroplane glazing, and helicopter windows. Many sanitary articles are also made from PMMA, such as basins, shower trays, bathtubs, shower compartments and mirrors. In addition, PMMA is widely known as the acrylic fibre used as synthetic wool in the clothing industry.)

Identification

PMMA burns readily with a yellow flame, giving off a pungent odour akin to burning *synthetic* wool.

B. Polycarbonate (PC)

Polycarbonate is an amorphous, and hence clear, material. PC is manufactured from bisphenol A (BPA). The benzene rings (C_6H_4) in the molecule's carbon "backbone" prevent it from bending or folding and give the polymer rigidity and temperature resistance. As a result, PC has unusually high impact strength (up to a temperature of 115°C) compared to other transparent amorphous materials. It can also be used at relatively extreme service temperatures, from -80°C to 140°C, and it can consequently be sterilised at 120°C. PC is resistant to petrol, oil, and greases. Other outstanding features are its creep resistance, dimensional stability, and natural self-extinguishing ability. Its optical clarity and high impact strength determine many end-uses (see below).

PC is, however, not indestructible. It is subject to attack (degradation) by strong acids, alkalis, amines, and aromatic hydrocarbons. Water, particularly hot water, corrodes PC, making it unsuitable for use in bathrooms and other applications where it may be submerged in hot water. PC yellows with time and is subject to UV attack in outside applications unless specially formulated to withstand weathering better by UV light.

Applications

Due to its excellent properties, PC is used in engineering and domestic applications (Figure 1.17B). Computer housings, sewing machine components, sight glasses (e.g., small windows to peek into tanks), filter cases, ventilation fans, electric razors, and mobile phone housings are all examples of PC applications. Photographic and audio apparatuses are further examples. Its optical properties make it ideal for glazing, protective glazing, balcony and bridge railings, bus and telephone shelters, greenhouse walling and armoured glass panels.

In the automotive industry, headlamps, ventilation and cooling grills, and hub caps are examples of PC. It is also used for safety (crash) helmets and visors. PC is not used for packaging, except sports-drink bottles and large 15 and 20-litre water fountain containers.

Identification

When dropped on a hard surface, a PC makes a sharp, metallic sound. It burns with a self-extinguishing yellow flame that smells of phenol. The material decomposes with little charring. While burning, the melt bubbles.

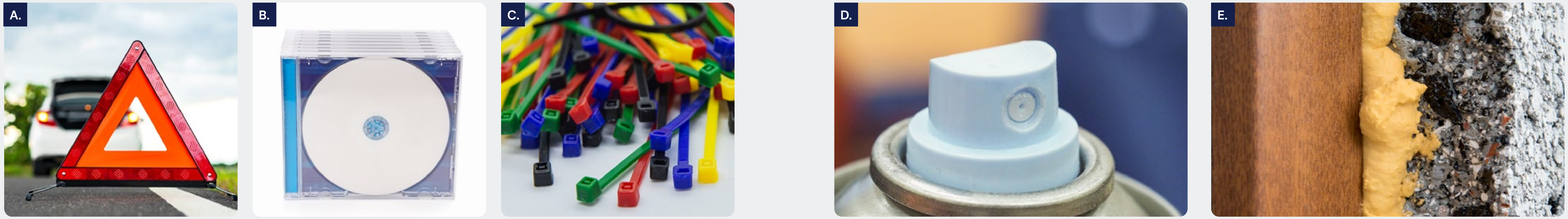


Figure 1.17: Examples of engineering plastics: A) PMMA, B) polycarbonate, C) polyamide, D) polyoxymethylene and E) polyurethane.

C. Polyamide (PA)

Polyamides are polymers that contain NH-CO linkages in the polymer chain. The different polyamides are distinguished by and named after the number of carbon atoms in their monomers. For example, PA 6 has six carbon atoms in each monomer. "Nylon" was originally a Du Pont trade name for polyamide materials used to replace silk. Today, though, nylon commonly refers to all the polyamide variants, which include products ranging from textiles and bristles to films and engineering components.

Another less common variant of PA is aromatic polyamides. These are used to manufacture high-tensile strength fibres, also called aramids; Kevlar®, the Du Pont trade name, is the best-known example used in bulletproof vests.

Polyamides are hard, stiff, tough, and abrasion-resistant materials. Another major property of this group is their internal lubricity and wear resistance, which accounts for many such applications as bearings, bushes, and gears (internal lubricity is achieved because the amide groups form loose bonds with surface moisture, which then act as a lubricant between the molecular chains). Lubricity can be increased further by adding PTFE (see *Fluoropolymers* in Section 1.5.6.F.) and molybdenum. Polyamides have good resistance to chemicals, especially hydrocarbons such as petrol, oil, and greases.

Nylon is popular because it is easily processed and can be modified into tailor-made grades for specific applications. Because of its low melt viscosity, PA can easily be formed into products requiring fine detail. Also significant is nylon's *fatigue resistance*, which is the ability to take repeated impacts over a long period without breaking. For comparison, polycarbonate may initially have a tenfold impact resistance but will break after a few impacts. Molecular orientation (Section 1.4.2.C.) significantly increases the tensile strength of nylon. Unidirectional-orientated filaments are used for fishing gut or rock-climbing ropes, for example.

PA does not have the best impact strength but can be reinforced with glass fibres and other toughening agents such as elastomers and plasticisers. Glass and talc-filled (reinforced) grades of PA also improve their heat resistance compared to unreinforced grades. PA lacks good resistance to some chemicals and will swell or dissolve in alcohol. In general, polyamides become less resistant to chemicals at higher temperatures.

Applications

Polyamides are used in various technical applications (Figure 1.17C). They are used to produce gears, rollers, screws, nuts, bearings, couplings, and sliders in machinery and appliances. In electronics, polyamides are used to manufacture coil cores, appliance housings, lamp housings, lighting fixtures, and cable plugs. PA plays a vital role in the automotive industry as intake manifolds, fan housings, oil filters, locks, carburettor parts, petrol pipes, safety belts, airbags, handles, and brake parts. Brushes, ropes and cables, fish netting, fishing line, dolls' hair, carpeting, edge trimmer cord, cable ties, castors and wheels, and zips are also made of PA. Their low permeability to gases and vapours makes PA materials eminently suitable for food packaging, where they are used in barrier films for processed meats and cheese. The thermal stability of PA makes it ideal for ovenable bags. The largest proportion of manufactured polyamides still go into the textile industry's yarn. Speciality grades of PA are used for high-performance fibres (Kevlar®) bulletproof vests or Nomex® and overalls for racing car drivers due to their superior heat and flame protection.

Identification

Polyamides can be identified by their high density relative to water and through a burn test:

- A small sample will sink in water.
- It burns with a yellow flame, which continues burning (unless flame retardant has been incorporated).
- The vapour smells of burning hair, and a sharp object easily pulls fine, long threads out of the molten material.
- Glass-filled grades can be identified by a gritty sound when scratched with a sharp object.

D. Polyoxymethylene or Polyacetal (POM)

Acetal, the common name for POM, is available as homopolymers and copolymers. This was the first thermoplastic material with metal-like properties capable of replacing non-ferrous metals with its stiffness, high-temperature performance, and low creep and wear properties. POM shares many of PA's properties, being strong and tough while retaining its properties at elevated temperatures. Dimensionally, it is stable and exhibits little creep. Its internal lubricity makes it fairly wear-resistant, especially if used with steel. POM slides easily on itself. It also exhibits good recovery from deformation, making it a good material for snap fits and springs.

Water absorption by acetal is significantly lower than in polyamides, but it should still be dried before processing. Solvent resistance is good, but strong acids and alkalis will attack acetal. Acetal produced for outdoor use requires additives to make it UV resistant. It is also relatively difficult to colour acetal and may need additional dyeing after forming. General-purpose acetal grades become brittle when in contact with non-ferrous metals.

Applications

POM has low creep, and combined with its low frictional properties and good abrasion resistance, it is an excellent engineering material. POM is typically used for gear wheels, springs, chains, screws, nuts, snap and press fittings, isolators, levers, hinges, rollers for sliding doors, curtain hooks, rugby and soccer boot studs and stud-housings, belt clips, aerosol valves, and more.

Identification

POM can often be identified purely based on its application: a hard, stiff polymer used to make small, white, hard-working components. Additionally, when dropped on a hard surface, POM objects make a sharp metallic sound. A burn test can provide further evidence to confirm a material as being POM:

- POM burns with a cold blue or clear (sometimes invisible) flame with a pungent odour. **Be careful when smelling the burnt residue, as it is often still burning!**
- The molten droplets continue to burn. It is best to burn the moulding over a bowl with water

E. Polyurethanes (PUR and TPU)

Polyurethanes are a family of highly diverse materials. Polyurethane polymers are created by the chemical reaction of two components at room temperature: isocyanate and polyol or OH-containing group. They range from rigid to flexible foams, and from elastomers to thin coatings, and even glues, varnishes, and fibres (Table 1.2). In fact, polyurethanes are so diverse they include both thermoplastics (TPU) and thermosetting plastics (PUR). For convenience, both types are discussed here. As can be expected, the properties of the different types of polyurethanes vary greatly, but they can be subdivided into three broad groups, namely rigid foams, flexible foams, and elastomers.

Rigid foams are one of the best thermal and acoustic insulation materials. They have excellent *adhesion* to wood, metals, glass, and fabrics, with a high strength-to-weight ratio. The properties of flexible foams depend on their foam density. Generally, flexible foams offer fast recovery from deformation; the moment you get up from your seat, the foam seat shape is restored. They also offer good adhesion properties and skid resistance with other materials, as can be seen in polyurethane soles that are "glued" onto the uppers with polyurethane adhesives offering excellent grip. As for rigid foams, flexible foams have good thermal and acoustic insulation.

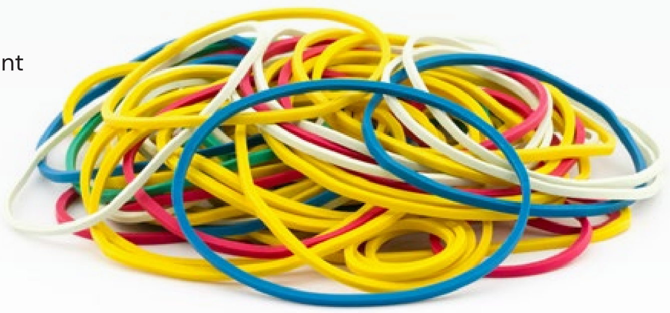
Applications

Polyurethanes represent such a large variety of products, so we only list the more common formats here (Table 1.2; see also Figure 1.17E).

Table 1.2: Examples of common formats of polyurethanes.

Type	Application
Rigid foam	• Insulation boards • Roofing and building panels • Imitation wooden products, refrigerator insulation • Cavity wall-filling
Semi-rigid foams (high impact)	• Carpet backings • Dashboard, spoilers • Roof coatings
Flexible foams	• Mattresses • Car seats, furniture cushioning • Sponges
Integral skin foams • Rigid • Semi-flexible • Micro-cellular elastomers	• Door panels – wood grain finish, TV cabinets • Steering wheels, car bumpers • Vibration absorbers
Thermoplastic elastomers	• Mining screens, castor tyres, seals • Bellows • Hose liners (inner and outer), tubing • Coated fabrics, sheeting
Thermosetting elastomers	• Coal mine chutes, the back of pick-up trucks • Caulking or sealing compounds • Encapsulated electronic parts, conveyor rollers • Skateboard wheels
Adhesives	• Can be used effectively on various substrates such as wood, stone, metal, ceramic, foam, glass, concrete, and lots more.
Thin coatings and paints	• Floor and porch paints • Durable external concrete coatings
Fibres (Spandex® or Elastane®)	• Garments where comfort and fit are required, such as hosiery (stockings), swimsuits, exercise wear, socks, surgical hose, undergarments, gloves, cycling shorts, wrestling suits, stretch types of denim, etc.

Elastomers (both thermoplastic and thermosetting) have excellent *abrasion* and *tear resistance*. They can absorb shock well and carry heavy loads. Elastomers can vary from incredibly soft to hard. However, they will degrade with a build-up of heat, and large, thick products cannot be used where high temperatures are frequently observed; for example, polyurethane elastomers are unsuitable for car tyres.



Identification

Polyurethanes can be identified with a burn test: A bright yellow, candle-like flame with a blue base gives off acrid fumes. The melt of TPU is brown-black in colour, fluid, and drops away quickly. A sharp object easily pulls fine elastic threads out of the molten material.

F. Fluoropolymers

Polytetrafluoroethylene (PTFE) is one of a family of fluorinated plastics, which share several properties. Other fluorinated plastics include:

- Tetrafluoroethylene/hexafluoropropylene copolymer (FEP)
- Polychlorotrifluoroethylene (PCTFE)
- Poly(vinyl fluoride) (PVF)
- Poly(vinylidene fluoride) (PVDF)
- Perfluoro alkoxyl alkane (PFA)

PTFE is a good example of the main properties of fluoropolymers:

- It has the highest chemical resistance of any material. While it may swell slightly, it is not truly attacked.
- It never really melts but softens slowly over a wide range of temperatures (80 to 260°C). This also means that it cannot be processed by normal methods[11].
- It has an extremely slippery surface – more slippery than ice on ice.

PTFE, specifically, also has excellent electrical properties (e.g., good insulating properties). On the other hand, its creep, wear, and abrasion resistance are poor.

Note: PTFE can give off toxic fumes if burnt in an open flame.

Applications

Fluoropolymers are used to produce a range of specific components:

- Sintered billets can be machined into fittings and connectors for high-service temperature applications, e.g., oven gaskets and door seals.
- Skived tape (i.e., tape cut into thin layers) is used for plumbing thread-sealing.
- Heat-sealing tapes are made from PTFE-coated glass-fibre scrim.
- Teflon® coated metal cooking utensils offer non-stick properties at high temperatures.

Identification

Fluoropolymer materials have a substantial waxy feel, which is impossible to ignite with a normal flame.

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[11] PTFE powders are normally compression moulded into short circular (billets) and then sintered for 24 hours in an oven before being machined into their final shape.

1.5.7. THERMOSETTING POLYMERS

When heated, a thermosetting plastic becomes irreversibly rigid. Initially, the polymer is a powder, liquid, or dough. Heating the material initiates a chemical reaction that initiates cross-linking between the polymer chains, and the material cures into a solid. The curing rate may increase along with raised pressure or by adding a catalyst. Thermosets, because of their irreversible format change, cannot be recycled.

A. Phenoplasts or phenol formaldehyde (PF)

Phenoplasts – also called phenolics, phenol formaldehyde, and Bakelite® – were once more common than they are now. Although they are still commercially important, PF plastics suffer from unprofitable processing methods. Phenoplast polymers, made available to converters as moulding powders, are used to create items of intricate designs that are dimensionally stable (creep resistant) and durable. Depending on the filler type, they can withstand 150°C and some intermittent temperatures as high as 260°C. They are good thermal and electrical insulators. Phenoplasts are sufficiently durable for outdoor use. They are also resistant to water and a wide range of solvents, fats, and oils but are attacked by acids and alkalis. Unfortunately, they are only available in dark colours, thus limiting their applications and reducing their popularity.

Applications

Compression moulded PF components include pot handles, stove knobs, circuit breakers, and bottle tops. Even at high temperatures, their water and fungus resistance and dimensional stability make PF adhesives effective in plywood, grinding disks, and non-softening brake pads (Figure 1.18A).

Identification

Phenoplasts have the following identifying characteristics:

- The moulding is always cold to the touch;
- It is impossible to cut off thin slivers of this plastic. Instead, cutting results in small powdery chips;
- A flame will turn yellow and produce a burnt electric appliance smell, and;
- The material does not continue to burn when the flame is removed.

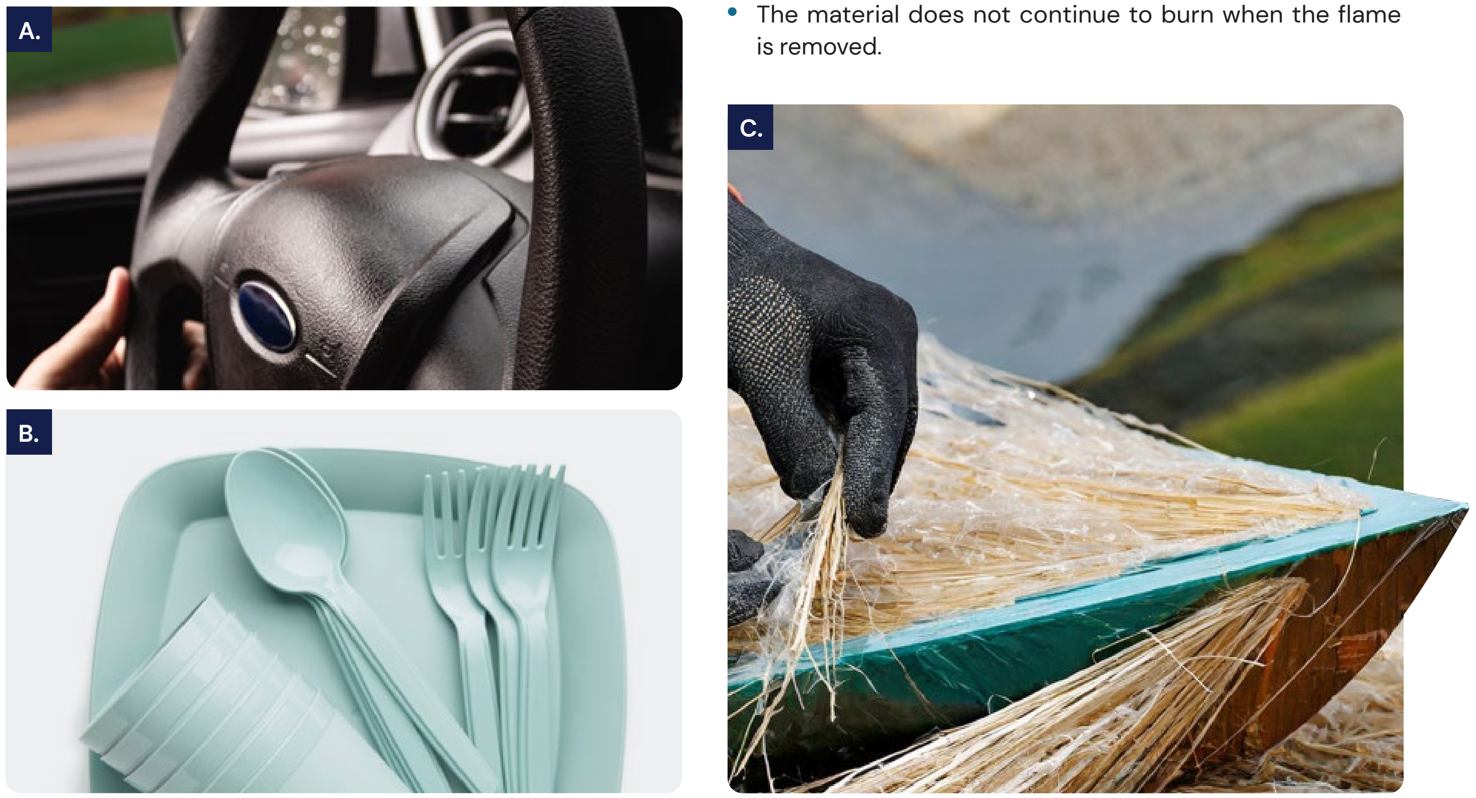


Figure 1.18: *Examples of thermosetting plastics: A) Phenoplasts and B) aminoplasts and C) unsaturated polyesters.*

B. Aminoplasts: Urea formaldehyde (UF) and melamine formaldehyde (MF)

Aminoplasts (or aminoplastics) are polymers formed by combining formaldehyde with a nitrogen molecule and an aliphatic alcohol (but we will not go into the chemistry here). Aminoplasts are produced as moulding powders, which are then used by converters to produce specific products. These moulding powders resemble phenoplasts but can be coloured and are not only available in dark colours. There are two groups of aminoplasts: urea formaldehyde (UF) and melamine formaldehyde (melamine or MF).

UF moulding powder is quite similar to PF but with lower water resistance and less impact resistance. Compared to PF, urea formaldehyde has a harder surface and better electrical properties (especially tracking and arc resistance required in high-voltage circuit breakers). UF is also used in adhesives.

Melamine has a better heat resistance and electrical properties than urea formaldehyde but is more expensive. It is stain resistant and does not yellow over time, and therefore has significant applications in food and household applications, including heat, scuff, and stain-resistant countertop coatings. It is softer and scratches easier than UF. Consumers, however, love the feel of melamine crockery and cutlery as it gives the impression of expensive, durable materials and does not feel like plastic. As an adhesive, melamine is more expensive than UF and water-resistant for applications involving bonding wood particles and laminates.

Applications

UF and MF have several applications for home use (and beyond), both as mouldings and adhesives (Figure 1.18B):

- MF is used for crockery for its non-plastic *feel* and stain resistance.
- UF toilet seats and light switches are used for dimensional stability, colours, and tracking resistance.
- Both UF and MF are used for knobs, handles, and bottle tops.
- UF adhesives and coatings are used for plywood and particleboard because of their light colour and hardness. MF composite wood board finishes are more water—and heat-resistant, e.g., melamine countertops.

Identification

UF and MF can be identified by cutting and burning:

- Cutting off a piece of moulding produces powdery chips; cutting off a sliver (a characteristic of thermosets) is impossible.
- When set alight, the flame will turn yellow with a light green edge, producing a fishy smell.
- UF and MF do not continue to burn after the flame is removed.

C. Unsaturated polyesters (UP)

Unsaturated polyesters, or resins, have been reinforced by glass fibres for so long that they are generally referred to as *glass fibre resins*. Glass-reinforced polyesters (GRP), or fibre-reinforced polyesters (FRP), can be made without expensive equipment and have become a popular way of making canoes, boats, and canopies, even as *do-it-yourself* projects.

Unsaturated polyester resin (UP) is produced by reacting and blending dibasic acid with glycol (again, we will avoid an in-depth chemistry discussion here). The UP chains are usually dissolved in styrene monomer. After adding an initiator or accelerator (to start the process), the styrene is polymerised causing cross-linking between chains (while in storage, though, inhibitors are added to prevent cross-linking occurring at room temperatures). When ready to be worked, a catalyst is added and mixed in. After mixing, the resin is then applied to the fibres. The hardened mixture of polyester resin and glass, built in layers, is called a laminate or composite. These composite materials have excellent structural properties. They weather well (if suitably modified) and show excellent impact and tensile strength. UP can also be used in high-voltage applications, and its chemical resistance is useful.

The most used reinforcing fibre is glass, which has various forms for different applications. Normally, liquid resin is applied to the glass. However, certain forms of fibre pre-impregnated with resin are supplied for specific high-volume production methods or critical applications. *Prepreg* is the generic term for these.

Applications

Strength and durability make glass fibre resins suitable for the manufacture of swimming pools, tanks, silos, and liners. Prepregs are used for car bonnets and large electrical components and enclosures. Prepregs' excellent strength-to-weight ratio, ease of construction, design, and colour variation versatility make it popular for the construction of canoes, yacht hulls, structural beach buggy bodies, and containers.

- Hand lay-up can be used to manufacture canoes, yacht hulls, structural beach buggy bodies, and containers as it offers ease of construction, good strength vs. weight, design variation, engineering and building modification, colour changes, etc.
- In spray-up, swimming pools, tanks, silos, and liners are made, as it offers a quicker process with wall thickness variations.
- Prepregs (SMC and DMC) are used for car bonnets, large electrical components, and enclosures.
- Pultruded profiles, made from glass fibre, can be used for guard rails, cable racking, and catwalks.
- Large diameter pipes, tankers and silos are filament wound.

Identification

As unsaturated polyesters are seldom, if ever, used alone, the application will often indicate the material used rather than the normal cut, burn, and smell test. Glass-reinforced polyesters are cold to the touch and do not feel like "plastic."

D. Epoxies (EP)

Epoxy resins are formed by reacting (i.e., combining) epichlorohydrin with an aromatic hydroxy compound such as bisphenol A (BPA). A catalyst (activator, hardener) is added to this resin, and cross-linking occurs at room temperature. Epoxy resins (EP) are the base of many common adhesives but also have a range of coating and moulding applications. As with polyester resins, glass fibres are used as reinforcement.

Aramid and carbon fibres have found increasing application areas, especially in aerospace and high-temperature applications (250°C). Adhesion to various substrates, especially metals and their ability to cure underwater make them extremely versatile materials. Epoxies' adhesion and shear strength are excellent, and their chemical resistance is higher than that of unsaturated polyesters. The properties of EP are influenced by the type of hardener used to manufacture them, making it possible to produce a particular combination of toughness, impact, chemical, heat, electrical resistance, flexibility, and adhesive strength.

Applications

Epoxies are so versatile that this is only a short list of their applications:

- Adhesives;
- Two-component moulding putties (machinable, hard, chemical, and temperature resistance);
- Floor binders due to water and abrasion resistance;
- Coatings for metal drums and cans, as it offers corrosion resistance, is non-toxic (when cured), tasteless, odourless and heat resistant;
- Encapsulation (housing) of electronic components;
- Composites: carbon reinforced jet engine pods, car drive shafts, helicopter blades, and;
- Prototype moulds for injection moulding.
- They are also available as a variety of repair putties, grouts, cold weld pastes, primers, and paints.

Identification

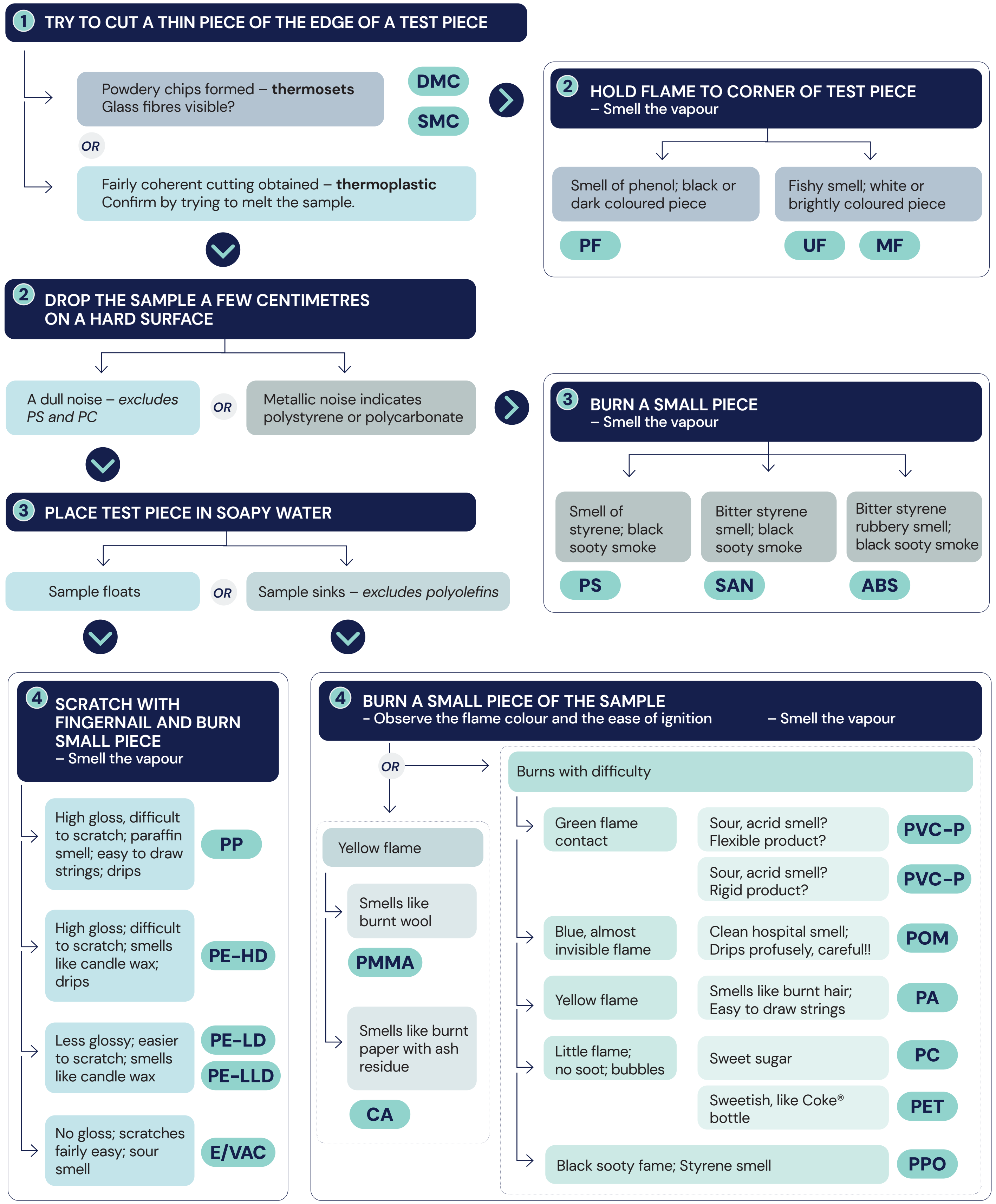
When set alight, epoxies continue to burn with a sooty smoke and luminous flame while giving off a phenol odour.

NOTE: Epichlorohydrin is a carcinogen (can cause cancer) and mutagen (can cause mutations). **Handle with extreme caution.** Clean, well-ventilated workshops are essential. Work surfaces should be covered in white or buff-coloured paper to detect spillages. Disposable containers should be used for mixing resins. Overalls, gloves, aprons, and, where necessary, breathing masks must be worn. The resins are flammable, so keep them away from open flames or smoking.

1.5.8. A QUICK AND SIMPLE KEY TO IDENTIFYING CONVENTIONAL PLASTICS

It is possible to perform simple tests to distinguish among the different thermoplasts and thermosets discussed earlier (see Table 1.3). These simple "experiments" are a great way to develop a better appreciation of the differences among the various plastics. Note, though, that burning plastics can be dangerous. When you burn mouldings, do so with a small piece at a time, in a well-ventilated area with no risk of a fire spreading, and do not inhale any fumes (plastics should not be burned routinely).

Table 1.3: A simple identification key for common plastics (adapted from Plastics SA; used with permission). Follow the numbered instructions.



① TRY TO CUT A THIN PIECE OF THE EDGE OF A TEST PIECE

- Powdery chips formed – **thermosets**
Glass fibres visible? → **DMC**, **SMC**
  - **② HOLD FLAME TO CORNER OF TEST PIECE** – Smell the vapour
    - Smell of phenol; black or dark coloured piece → **PF**
    - Fishy smell; white or brightly coloured piece → **UF**, **MF**
- OR
- Fairly coherent cutting obtained – **thermoplastic**
Confirm by trying to melt the sample.

② DROP THE SAMPLE A FEW CENTIMETRES ON A HARD SURFACE

- A dull noise – *excludes PS and PC*
- OR
- Metallic noise indicates polystyrene or polycarbonate
  - **③ BURN A SMALL PIECE** – Smell the vapour
    - Smell of styrene; black sooty smoke → **PS**
    - Bitter styrene smell; black sooty smoke → **SAN**
    - Bitter styrene rubbery smell; black sooty smoke → **ABS**

③ PLACE TEST PIECE IN SOAPY WATER

- Sample floats
- OR
- Sample sinks – *excludes polyolefins*

④ SCRATCH WITH FINGERNAIL AND BURN SMALL PIECE – Smell the vapour

- High gloss, difficult to scratch; paraffin smell; easy to draw strings; drips → **PP**
- High gloss; difficult to scratch; smells like candle wax; drips → **PE-HD**
- Less glossy; easier to scratch; smells like candle wax → **PE-LD**, **PE-LLD**
- No gloss; scratches fairly easy; sour smell → **E/VAC**

④ BURN A SMALL PIECE OF THE SAMPLE – Observe the flame colour and the ease of ignition – Smell the vapour

- Yellow flame
  - Smells like burnt wool → **PMMA**
  - Smells like burnt paper with ash residue → **CA**
- OR
- Burns with difficulty
  - Green flame contact
    - Sour, acrid smell? Flexible product? → **PVC-P**
    - Sour, acrid smell? Rigid product? → **PVC-P**
  - Blue, almost invisible flame – Clean hospital smell; Drips profusely, careful!! → **POM**
  - Yellow flame – Smells like burnt hair; Easy to draw strings → **PA**
  - Little flame; no soot; bubbles
    - Sweet sugar → **PC**
    - Sweetish, like Coke® bottle → **PET**
  - Black sooty fame; Styrene smell → **PPO**

1.6.

Bioplastics

Bioplastics, often considered a more environmentally friendly alternative to conventional plastics, are used in an increasing number of markets. Packaging remains the largest field of application, with 1.15 million tonnes (48%) of the total bioplastics market in 2021 globally[12] used for packaging. However, the portfolio of applications continues to diversify. Segments, such as automotive and transport or building and construction, significantly increased their share. In principle, they could replace many applications for petroleum-derived plastics, but cost and performance remain problematic. Their use is financially favourable only if supported by specific regulations limiting the usage of conventional plastics.

However, the term "bioplastics" is ambiguous and often misunderstood by consumers. The term is typically used interchangeably with "biobased", "biodegradable", and "compostable" plastics. Misconceptions about what they are leads to the incorrect use and disposal of bioplastic waste. In its most general definition[13], bioplastics are polymers that are bio-based and/or biodegradable. We take a closer look at what this means, below (see Van Hille 2020 for more information about bioplastics).

1.6.1. BIO-BASED POLYMERS

Bio-based polymers are defined as plastics derived directly or indirectly from renewable sources (i.e., plant-based biomass) such as vegetable oil, corn-starch, potatoes, pea starch, sugar, etc. (Ashter 2016), and even from animals, such as chitin from crustacean exoskeletons (Nandakumar et al. 2021). They often include many distinct plastic types rather than one polymer. Biobased polymers can be either biodegradable or non-biodegradable, depending on their specific monomers (Figure 1.19).

Some bio-based plastics may be identical to fossil fuel-based polymers (e.g., PET, PE, PP). In this case, the monomers (e.g., ethylene or propylene) are produced from plant-based materials rather than fossil fuels. Some examples are Bio-PET, Bio-PE, and Bio-PP. These plastics can be recycled with conventional fossil fuel-based plastics and are non-biodegradable.

Other bio-based plastics are completely different from conventional polymers. Some examples include polylactic acid (PLA), polyhydroxyalkanoate (PHA), and thermoplastic starch. These bioplastics can be derived from food crops such as corn, potatoes, and sugar cane, and they are considered first-generation bio-based plastics. Second-generation bio-based plastics are derived from non-food crops, organic waste, or agricultural by-products. Some bioplastics, such as cellulose derivatives, e.g., cellulose acetate, have been used for a long time, but new types are being developed.

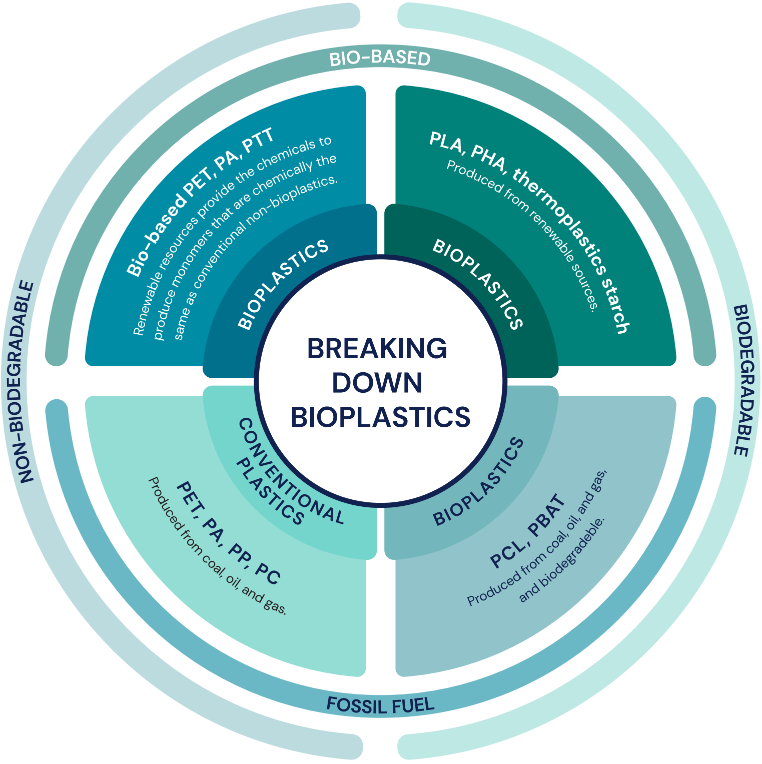


Figure 1.19: *The relationship between biobased, biodegradable, and conventional polymers. Note: plastics with prodegradant additives are excluded from this graph.*

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[12] See https://www.european-bioplastics.org/market/ [Accessed in December 2022]

[13] Not all organisations define bioplastics the same. European Bioplastics, for example, uses the broad definition given here, while Plastics SA limits the definition of bioplastics to bio-based plastics.

1.6.2. BIODEGRADABLE POLYMERS

The biodegradability of plastics does not depend on the origin of their raw material, i.e., it does not matter whether a plastic is petrochemical or bio-based. As discussed above, some bio-based plastics are biodegradable. Some fossil-fuel-based plastics are also biodegradable. Examples are polybutylene adipate terephthalate (PBAT) and polycaprolactone (PCL) (Nandakumar et al. 2021). The ability to biodegrade is directly linked to the chemical structure of the polymer.

A **biodegradable** plastic is converted into water, carbon dioxide (in the case of aerobic biodegradation) and possibly methane (under anaerobic conditions), and biomass by microorganisms over months rather than years. Biodegradable plastics are not necessarily converted into good-quality compost. Certain biodegradable plastics are compostable, though.

A **compostable** plastic must satisfy specific criteria, i.e., 90% of the material must biodegrade within six months, it must not produce any toxic material, and the compost must be able to support plant growth. Plastics may be home-compostable or industrially compostable. Industrial composting requires controlled conditions, including a temperature between 50 and 70°C, forced aeration, and controlled humidity in an industrial composting facility; biodegradation must be completed within a specified timeframe.

Home composting has fewer specifications, and the process is less controlled, i.e., biodegradation must be completed under conditions found in a home compost pile. So, not all biodegradable plastics are compostable, but all compostable plastics are biodegradable.

It is misleading to claim a product is biodegradable or compostable with no standard specification. This can be seen as a form of greenwashing[14]. To become certified, products must undergo rigorous laboratory testing according to international standards by an independent third party[15]. Biodegradable plastics must conform to the standards DIN 38412:30 or ISO 14855-1, while the standards ISO 17088, EN 13432, or ASTM D6400[16] apply to compostable plastics. For example, the recently published South African standard SANS 1728:2019 specifies the requirements for marking and identifying biodegradable plastics. Incorrect or ambiguous labelling may result in improper disposal of plastic waste.

Biodegradable and compostable plastics are preferable when their alternatives are difficult or too expensive to recycle (Figure 1.20). Some examples include on-the-go-food packaging or feminine hygiene products.

Figure 1.20: *Examples of products labelled "biodegradable".*

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[14] Greenwashing is when a company intentionally (or sometimes, perhaps, not intentionally) make their product appear to be more sustainable and environmentally friendly than it is.

[15] See https://etsus.co/what-are-the-different-certifications-for-compostable-plastic/.

[16] See https://www.astm.org/d6400-21.html for a detailed description of ASTM D6400.

1.6.3. PLASTICS WITH PRODEGRADANT ADDITIVES

Attempts have been made to make conventional (fossil fuel-based, non-biodegradable) plastics more biodegradable by adding small amounts of prodegradant additives to these plastics when manufactured. The prodegradant additives speed up fragmentation of the plastics, thus allowing microorganisms to break them down more easily, at least in theory. Prodegradant additives include oxo-additives, which require oxidative conditions, and bio-additives, which require microbes to break the plastic down.

But there are concerns about the use of such prodegradant additives. Certain claims by manufacturers are unsubstantiated, and evidence for the complete biodegradation of these plastics is lacking. There are further concerns about the production of environmentally harmful microplastics, which can contaminate recycling streams.

A. Oxo-degradable additives

Oxo-degradable additives are a group of additives, often metal salts of carboxylic acids, which are marketed on the hypothesis that they accelerate the degradation of the polymer structure to produce fragments – microplastics - small enough that microorganisms can biodegrade them into CO_2 and water. On this basis, materials containing these additives are often called oxo-biodegradable. Plastics advertised as oxo-degradable (or oxo-biodegradable) are made from non-biodegradable plastics mixed with additives to initiate biodegradation. These products do not comply with compostability standards and, as such, cannot carry the seedling label associated with compostable materials.

Put simply, as the plastic is exposed to sunlight (UV light) and oxygen, heat, or stress, the polymers become brittle and disintegrate into microplastics. Microorganisms can then more easily biodegrade these fragments into their natural components. Oxo-additives have predominantly been used in films, such as bags and food packaging, in countries with limited post-consumer collection and recycling infrastructure. It is not certain if or how efficiently microorganisms degrade these fragments.

B. Bio-additives

Bio-additives are a group of proprietary molecules (e.g., BioSphere®) added to plastic polymers to make them more easily biodegraded by bacteria. These additives are touted to reduce the hydrophobicity (the tendency to repel water) of the plastic, making it easier for microbes to attach and initiate degradation processes since bacteria require water to function. As the plastic fragments, more microorganisms can attach to them, breaking them down further. Therefore, the overarching mechanism resembles that of oxo-degradable materials, with the major difference being that the initial degradation is not induced by heat, UV, and oxygen but rather by microbial action.

Bio-additives have not been on the market as long as oxo-additives, and independent scientific studies have yet to verify the claims by manufacturers. For example, manufacturers claim, without providing evidence, that the additives do not promote fragmentation. Another claim is that, since plastics with bio-additives require bacteria to break them down (not UV and heat, as with oxo-degradable plastics), they pose less of a risk to the technical integrity of recycled products, as most are not designed for prolonged use in microbe-rich environments. However, knowing which plastic recyclate will be used in advance is difficult, making this a dangerous assumption. If they enter the recycling waste stream, there is a risk that plastics with bio-additives may negatively impact the quality and integrity of the recycled material.

1.6.4. ARE BIOPLASTICS GOOD FOR THE ENVIRONMENT (AND CONSUMERS)?

Most consumers have a limited awareness and understanding of what biodegradability and compostability mean and what is required for responsible consumer management. The absence of effective education and awareness can create the misconception that biodegradable materials decompose rapidly in the environment, potentially exacerbating a 'littering culture'. Brand owners, retailers, and consumers are typically unaware of the range of material types and their properties or that different materials may only be certified to degrade or compost under specific, controlled conditions.

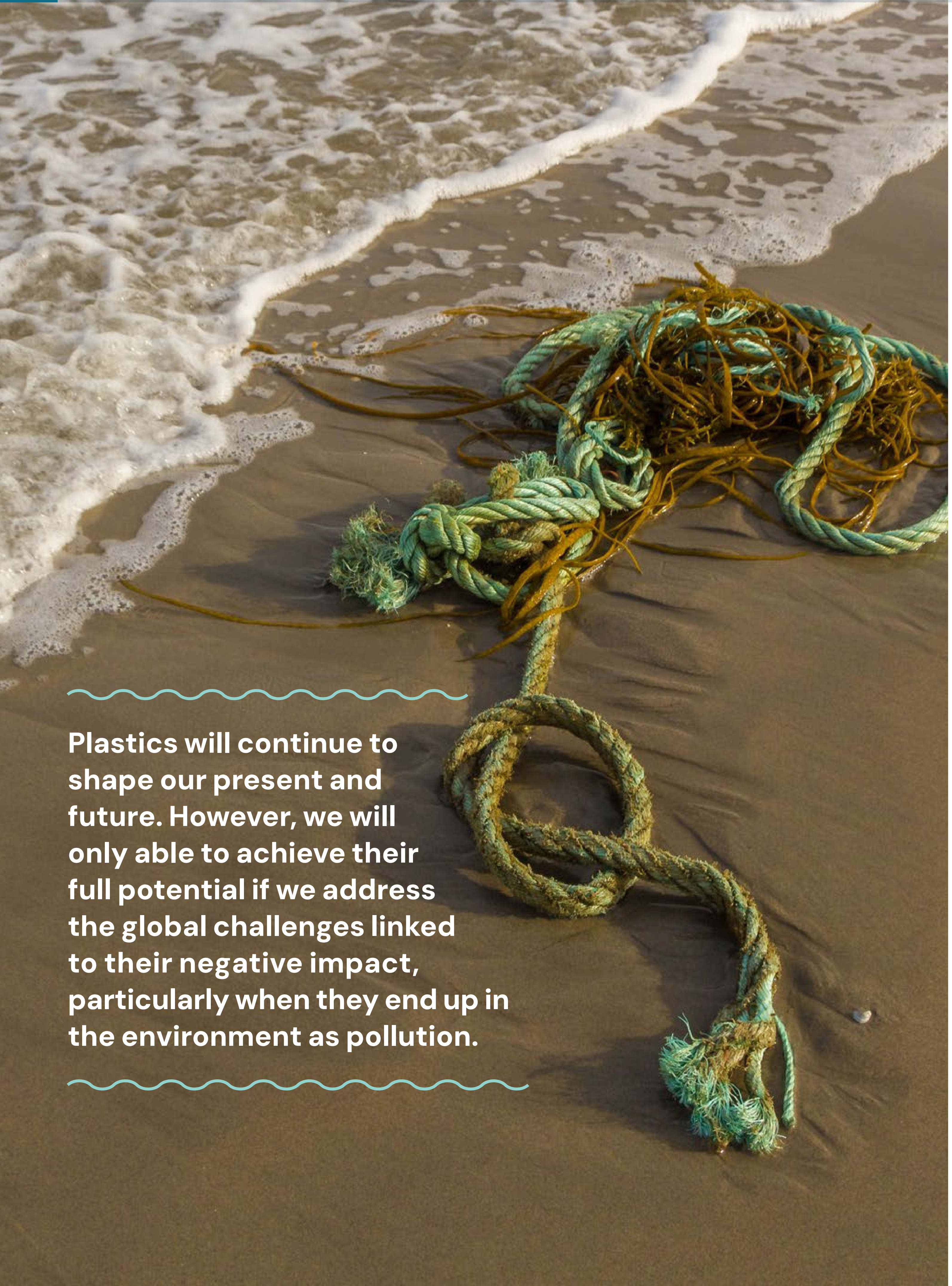
Currently, there is no economic incentive for informal waste pickers to collect biodegradable or compostable plastics from the environment, landfill, or household waste. Therefore, it is highly unlikely that these materials will be collected if they are disposed of through conventional means. There are a limited number of industrial composting facilities, and none of these are keen on accepting compostable products or packaging. Home composting facilities are only available to a small number of consumers.

In countries where mechanical recycling is the preferred end-of-life treatment for most plastics, there is a risk of contaminating the incoming waste stream with materials containing pro-degradants as they are labelled *recyclable*.

Marked compostable products and packaging should be removed from the recyclable waste stream and directed to the industrial composting facilities, if any.

Is there room for bio-based and biodegradable materials in society? Biodegradable plastics make sense in cases where recycling is not economical or practically viable. Still, these products must be coupled with education, awareness, adequate collection facilities and access to composting facilities.

There is also value in using renewable sources for bio-based plastic production rather than fossil fuel. In selecting the best material for any application, the availability of the material, the polymer characteristics, and the available end-of-life waste management options must be considered. All natural resources must be managed carefully, and every choice must be based on evidence that a particular material is the most resource-efficient across its entire life cycle.



Plastics will continue to shape our present and future. However, we will only able to achieve their full potential if we address the global challenges linked to their negative impact, particularly when they end up in the environment as pollution.

1.7.

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