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Plastic pollution and potential solutions

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ABSTRACT

A review is presented of the manufacture and use of different types of plastic, and the effects of pollution by these materials on animal, human and environmental health, insofar as this is known. Since 2004, the world has made as much plastic as it did in the previous half century, and it has been reckoned that the total mass of virgin plastics ever made amounts to 8.3 billion tonnes, mainly derived from natural gas and crude oil, used as chemical feedstocks and fuel sources. Between 1950 and 2015, a total of 6.3 billion tonnes of primary and secondary (recycled) plastic waste was generated, of which around 9% has been recycled, and 12% incinerated, with the remaining 79% either being stored in landfills or having been released directly into the natural environment. In 2015, 407 million tonnes (Mt) of plastic was produced, of which 164 Mt was consumed by packaging (36% of the total). Although quoted values vary, packaging probably accounts for around one third of all plastics used, of which approximately 40% goes to landfill, while 32% escapes the collection system. It has been deduced that around 9 Mt of plastic entered the oceans in 2010, as a result of mismanaged waste, along with up to 0.5 Mt each of microplastics from washing synthetic textiles, and from the abrasion of tyres on road surfaces. However, the amount of plastics actually measured in the oceans represents less than 1% of the (at least) 150 Mt reckoned to have been released into the oceans over time. Plastic accounts for around 10% by mass of municipal waste, but up to 85% of marine debris items – most of which arrive from land-based sources. Geographically, the five heaviest plastic polluters are P.R. China, Indonesia, Philippines, Vietnam and Sri Lanka, which between them contribute 56% of global plastic waste. Larger, primary plastic items can undergo progressive fragmentation to yield a greater number of increasingly smaller 'secondary' microplastic particles, thus increasing the overall surface area of the plastic material, which enhances its ability to absorb, and concentrate, persistent organic pollutants (POPs) such as dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyls (PCBs), with the potential to transfer them to the tissues of animals that ingest the microplastic particles, particularly in marine environments.

Although fears that such microparticles and their toxins may be passed via *food webs to humans are not as yet substantiated, the direct ingestion of microplastics by humans* via *drinking water is a distinct possibility – since 92% of samples taken in the USA and 72% in Europe showed their presence – although any consequent health effects are as yet unclear. Foodstuffs may also become contaminated by microplastics from the air, although any consequent health effects are also unknown. In regard to such airborne sources, it is noteworthy that small plastic particles have been found in human lung tissue, which might prove an adverse health issue under given circumstances. It is also very striking that microplastics have been detected in mountain soils in Switzerland, which are most likely windborne in origin. Arctic ice core samples too have revealed the presence of microplastics, which were most likely carried on ocean currents from the Pacific garbage patch, and from local pollution from shipping and fishing. Thus, sea ice traps large amounts of microplastics and transports them across the Arctic Ocean, but these particles will be released into the global environment when the ice melts, particularly under the influence of a rising mean global temperature.*

While there is a growing emphasis toward the substitution of petrochemically derived plastics by bioplastics, controversy has arisen in regard to how biodegradable the latter actually are in the open environment, and they presently only account for 0.5% of the total mass of plastics manufactured globally. Since the majority of bioplastics are made from sugar and starch materials, to expand their use significantly raises the prospect of competition between growing crops to supply food or plastics, similarly to the diversion of food crops for the manufacture of primary biofuels. The use of oxo-plastics, which contain additives that assist the material to degrade, is also a matter of concern, since it is claimed that they merely fragment and add to the environmental burden of microplastics; hence, the European Union has moved to restrict their use.

Since 6% of the current global oil (including natural gas liquids, NGLs) production is used to manufacture plastic commodities – predicted to rise to 20% by 2050 – the current approaches for the manufacture and use of plastics (including their end-use) demand immediate revision. More extensive collection and recycling of plastic items at the end of their life, for re-use in new production, to offset the use of virgin plastic, is a critical aspect both for reducing the amount of plastic waste entering the environment, and in improving the efficiency of fossil resource use. This is central to the ideology underpinning the circular economy, which has common elements with permaculture, the latter being a regenerative design system based on 'nature as teacher', which could help optimise the use of resources in town and city environments, while minimising and repurposing 'waste'. Thus, food might be produced more on the local than the global scale, with smaller inputs of fuels (including transportation fuels for importing and distributing food), water and fertilisers, and with a marked reduction in the use of plastic packaging. Such an approach, adopted by billions of individuals, could prove of immense significance in ensuring future food security, and in reducing waste and pollution – of all kinds.

Keywords: *plastics, plastic pollution, plastic waste, polymer, ocean gyre, Great Pacific garbage patch, microplastics, nanoplastics, nurdles, plastic recycling, circular economy, compostable plastics, bioplastics, biodegradable plastics, marine debris, marine litter, marine pollution, plastic manufacture, permaculture*

1. Introduction and history

In the classic film, *The Graduate*, a family friend, Mr McGuire, cryptically exhorts the eponymous graduate, Benjamin, to consider a career in the plastics industry, according to the following dialogue[1]:

Mr McGuire: ‘I just want to say one word to you. Just one word.’
Benjamin: ‘Yes, sir.’
Mr McGuire: ‘Are you listening?’
Benjamin: ‘Yes, I am.’
Mr McGuire: ‘Plastics.’
Benjamin: ‘Exactly how do you mean?’
Mr McGuire: ‘There’s a great future in plastics. Think about it. Will you think about it?’

When the film was released in 1967, the global primary production of plastics amounted to around 23 million tonnes (Mt) (see ref. 2), but this had risen to 407 Mt in 2015[2], which corresponds to a compound annual growth rate of around 8%. Since 2004, the world has made as much plastic as it did in the previous half century[2]. The materials that we commonly call plastics are high molecular mass, synthetic organic polymers, mainly derived from hydrocarbons obtained from crude oil and natural gas, and while they are employed for a large variety of purposes, more than one third of the entire mass of plastics produced globally is used to make packaging, which typically is not recycled, but instead ends up as waste[2]. There are two principal kinds of plastic: thermoplastic[3], which can be moulded repeatedly on heating, such as (high and low density) polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC) and polystyrene (PS) – including ‘expanded polystyrene’; and thermoset[4], which once formed, cannot be heated and remoulded, for example, polyurethane (PUR) and epoxy resins or coatings. Plastics are commonly manufactured from fossil fuels, but biomass (*e.g.* maize, plant oils) is increasingly being used (Section 9.5): once the polymer is synthesised, its properties will be the same whatever the type of raw material used (*i.e.* PE will have the same properties, whether it is made from ethylene derived from fossil or biological sources). The first synthetic plastic is considered to be Parkesine (a form of nitrocellulose; Figure 1) which was first produced[5] in the UK by Alexander Parkes, in 1856, by treating cellulose with nitric acid. The product of this (called cellulose nitrate, or pyroxylin) could be dissolved in various organic solvents, the removal of which resulted in a transparent solid material that became mouldable on heating (thermoplastic), and a ‘synthetic ivory’ could be made from it[5]. Improvements to the invention for making ‘masses or sheets [of Parkesine], or to spread the combinations on textile or other fabrics to produce waterproof cloth’ were described in an 1865 patent[6]. In 1869, the American inventor John Wesley Hyatt produced ‘celluloid’, by adding camphor to nitrocellulose as a plasticiser, with the result that it could be fabricated into a photographic film[5]. Celluloids were used extensively in the photographic and cinematographic industries, and Eastman marketed the first motion picture film on nitrate base, in 1889. The material was also known as ‘nitrate film’, but was notoriously unstable and inflammable leading to numerous fires, and hence ‘safety film’ (cellulose acetate film) was introduced in 1908 as a much safer substitute: the latter was used in 1924 for recording X-ray images, and by 1950 it had practically replaced nitrate as a film for motion pictures[7].

Two serendipitously discovered new types of plastics were PVC[8] in 1872, and polyethylene[9] in 1898, although they were not produced commercially until some decades later. The first fully synthetic thermosetting resin was made in the early 1900s by condensing formaldehyde with phenol, and named Bakelite[10] by/after its discoverer, Leo Baekeland. The technological advances in chemistry that were driven by the First World War, led to the creation of many new and different types of plastics, which were subsequently mass produced. In Table 1, is shown a timeline sketch for the development of plastics during the 20th century[11].

Our awareness that most plastics contain organic polymers of high molecular mass is due to Hermann Staudinger, who is sometimes referred to as 'the father of polymer chemistry'. Staudinger coined the term 'macromolecule', and demonstrated the existence of such very large molecular species (as opposed to highly associated numerous smaller molecules) for which he was awarded the Nobel Prize in Chemistry[12] in 1953. On the basis of physical methods, such as freezing point depression, very high molecular weights had been determined for rubber, and in a groundbreaking paper published in 1920, Staudinger proposed that the structures of rubber, starch, cellulose, and proteins consist of long chains of short repeating molecular units linked by covalent bonds[13]. Hence, polymer chains are analogous to chains of paper clips, being linked from end to end *via* repeating smaller units (Figure 2).

Staudinger's revolutionary idea was initially opposed by members of the scientific establishment, who did not believe that small molecules could undergo the highly extensive covalent bonding required to form such very large molecules. Indeed,

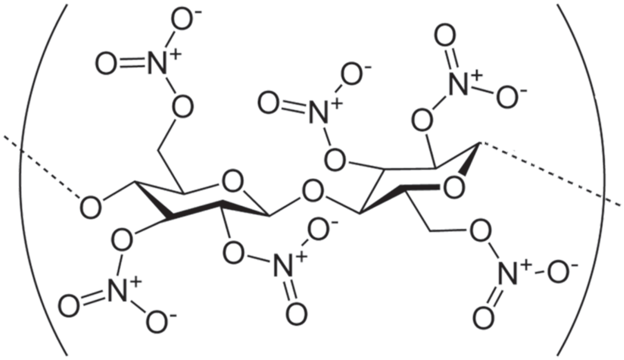

***Figure 1** Molecular structure of nitrocellulose. Credit: Meitnerium, https://upload.wikimedia.org/wikipedia/commons/8/83/Nitrocellulose-2D-skeletal.png.*

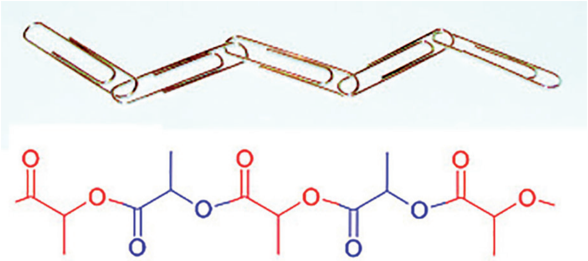

***Figure 2** A polymer such as polylactic acid can be viewed in analogy with a chain of paper clips, where the polymer chain is composed of linked, repeating small monomer units. Credit: Evastars, https://upload.wikimedia.org/wikipedia/commons/8/86/Clipspla.jpg.*

***Table 1** Significant developments in the field of plastics during the 20th century*[11]

Year	Event
1907	The first fully synthetic thermosetting resin was made by condensing formaldehyde with phenol, and named Bakelite by/after its discoverer, Leo Baekeland.
1912	Cellophane was patented by its creator Jacques E. Brandenberger.
1926	While working at the B.F. Goodrich Company, Waldo Semon managed to plasticise PVC by blending it with various additives. The result was a more flexible and more easily processed material that soon achieved widespread commercial use.
1930	Neoprene was first manufactured by DuPont, under the name DuPrene.
1930s	Polystyrene was first manufactured by IG Farben (the precursor company to BASF).
1931	The vinyl-based material, Victrolac, was used by RCA Victor for manufacturing 'vinyl' records, which were an improvement on records made from shellac, with twice the groove density and good sound quality.
1933	The first industrially practical polyethylene synthesis was discovered by Eric Fawcett and Reginald Gibson, while working for the Imperial Chemical Industries (ICI) at Northwich, UK.
1935	The first nylon (nylon 6,6) was produced using diamines on 28 February 1935, by Wallace Hume Carothers, while working at DuPont. (Prompted by Carothers' work, Paul Schlack at IG Farben developed nylon 6 – based on caprolactam – on 29 January 1938.)
1938	Nylon was first used to make the bristles for toothbrushes. It featured at the 1939 world's fair, and in 1940, was famously used to make stockings ('nylons') from.
1938	Polytetrafluoroethylene (more usually called Teflon) was discovered by Roy Plunkett, an employee at DuPont.
1941	Polyethylene terephthalate (PET) was patented by John Rex Whinfield, James Tennant Dickson and their employer, the Calico Printers' Association of Manchester, UK.
1950	Polyester was first manufactured by DuPont.
1951	Polypropylene was formed by polymerising propene by J. Paul Hogan and Robert L. Banks, working at Phillips.
1953	Polycarbonate was developed independently by Hermann Schnell working at Bayer, and by Daniel Fox at General Electric.
1954	Propylene was first polymerised to a crystalline isotactic polymer by Giulio Natta, and also by the German chemist Karl Rehn.
1954	Expanded polystyrene was developed by the Koppers Company in Pittsburgh, Pennsylvania, under the trade name Dylite.
1957	The Italian firm Montecatini began large-scale commercial production of isotactic polypropylene.
1960s	High-density polyethylene bottles were introduced, which rapidly replaced glass bottles for most uses.
1965	Kevlar was developed by Stephanie Kwolek, working at DuPont.
1980s	Polyester film stock was used to replace cellulose acetate for photographic film and computer tapes.
1988	The first polymer bank notes were issued in Australia.

contemporary luminaries in organic chemistry, such as Emil Fischer and Heinrich Wieland, thought that numerous smaller molecules had merely aggregated to form colloids, and so the high molecular masses that had been measured were artefacts, rather than reflecting the dimensions of actual, large single molecules[14]. However, the macromolecule theory was finally vindicated by the pioneering X-ray diffraction studies of polymers[15], made by Herman Mark, which demonstrated directly the presence of long chains of repeating small molecular units. This work led to the formulation of the Mark–Houwink (or Mark–Houwink–Sakurada) equation[16], which connects the relative molecular mass of a polymer with its intrinsic viscosity. The fact that such polymers as nylon and polyester could be formed by direct chemical synthesis[17], reinforced the idea that they were made from macromolecules, and also that novel polymers could be designed and created by synthetic chemical means. Indeed, with considerable foresight, Staudinger himself commented[18] in 1936: 'It is not improbable, that sooner or later a way will be discovered to prepare artificial fibres from synthetic high-molecular products, because the strength and elasticity of natural fibres depend exclusively on their macro-molecular structure – *i.e.*, on their long thread-shaped molecules.'

It is from such beginnings that the world has been provided with a multiplicity of polymeric materials, including plastics and textiles, driven by the relentless demand for an ever greater range of cheaper and more seductive consumer products, while additionally providing structures and components of reduced weight, and greater durability for construction and engineering applications. Hence plastics are an intrinsic, and underpinning feature of contemporary global civilisation.

2. Types of plastics in use

2.1 Classification

The backbone of a polymer defines the longest, and continuous, molecular main-chain, as formed by the mutual interconnection of a very large number of repeating (monomer) units, generally into the thousands, or in some examples, hundreds of thousands (*e.g.* ultra-high-molecular-weight polyethylene; UHMWPE). The elemental composition of the backbone can either be all-carbon, or other atoms may be present, usually oxygen or nitrogen, and occasionally silicon or sulfur (Section 2.2). The particular properties of a plastic can be fine-tuned, according to the specific molecular repeating monomer unit that is used to construct the polymer backbone, and through the attachment of various different functional moieties along its length, generally referred to as side-chains. Plastics are generally categorised according to the essential form of the polymer backbone, and thus we have the various different kinds of polyethylene, polypropylene, polyacrylics, polyesters, polyamides, silicones, polyurethanes, and halogenated plastics, *e.g.* PVC. Plastics may also be classified by the type of synthetic method used to create them, *e.g.* polycondensation, polyaddition, cross-linking[19], and by such defining physical properties as, hardness, density, tensile strength, resistance to heat, and glass transition temperature. The chemical behaviour of a plastic, and its resistance towards such influences as organic solvents, oxidation, and ionising radiation, are also important factors in its selection or rejection for particular applications. Other descriptors for plastics are: thermoplastics and thermosets, conductive polymers, biodegradable plastics, engineering plastics, and elastomers, which refer to aspects of their design and manufacture.

2.2 Different types of plastics

The main types of plastics that are manufactured[2] are resins, *i.e.* polyethylene (116 Mt), polypropylene (68 Mt), polyvinyl choride (38 Mt), polyethylene terephthalate (33 Mt), polyurethane (27 Mt) and polystyrene (25 Mt), along with 59 Mt of (polyester, polyamide and acrylic) fibres, plus 25 Mt of 'additives'. However, a total of 16 Mt of 'other' plastics is also produced in great variety, as is indicated in Sections 2.2.1 and 2.2.2.

2.2.1 Common commodity and engineering plastics, and their uses[20]

Very many commonly used items are made from various types of plastics, for example those shown in Figures 3 and 4. The golf ball, shown in Figure 5, is an example of an object made from a combination of different plastics, consisting of

Figure 3 *A variety of household objects made out of plastic. From top left to bottom right: measuring cup, tape dispenser with tape, cooking timer, plastic jug, pill container, medical inhaler pump, plastic fold-top sandwich bag, crocodile clip, CD. Credit: ImGz, https://upload.wikimedia.org/wikipedia/commons/b/b2/Plastic_household_items.jpg.*

Figure 4 *Smartphone with a polycarbonate unibody shell. Credit: Kārlis Dambrāns, https://upload.wikimedia.org/wikipedia/commons/a/a6/IPhone_5c_blue_back.jpg.*

Figure 5 *Golf ball, consisting of a polybutadiene rubber core, surrounded by a hard, polyethylene ionomer resin shell. Credit: Karen Blakeman.*

a polybutadiene rubber core, surrounded by a hard ionomer resin shell. Some other representative examples of plastics in common use are given in the following list.

- Polyamides (PA) (including nylon): fibres, bristles for toothbrushes, tubing, fishing line and low-strength components, for example engine parts or gun frames.
- Polycarbonate (PC): compact discs, eyeglasses, riot shields, security windows, traffic lights, 'plastic' lenses, smartphone unibody shells (Figure 4).
- Polyester (PES): fibres and textiles.
- Polyethylene (PE): used to make cheap packaging and wrapping materials, along with disposable supermarket shopping bags, and plastic bottles.
- High-density polyethylene (HDPE): detergent bottles, milk jugs and moulded plastic cases, to contain various items.
- Low-density polyethylene (LDPE): garden furniture, floor tiles, shower curtains and clamshell packaging.
- Polyethylene terephthalate (PET): bottles to hold carbonated drinks, food jars, plastic films, and microwavable packaging.
- Polypropylene (PP): bottle caps, drinking straws, yogurt containers, household appliances, tables and chairs, car bumpers (fenders) and pipe systems designed to withstand pressure.
- Polystyrene (PS): loose foam packaging, food containers, plastic tableware, disposable cups, plates and cutlery, boxes for compact discs and cassettes.
- High impact polystyrene (HIPS): refrigerator liners, food packaging and vending cups for drinks.
- Polyurethanes (PU): foams for cushioning, foams to provide thermal insulation, surface coatings, rollers for printing, and is the most common plastic currently used in cars.
- Polyvinyl chloride (PVC): pipes for plumbing and guttering, doors, and frames for doors and windows, flooring material, shower curtains.
- Polyvinylidene chloride (PVDC): food packaging film, such as Saran.
- Polybutadiene: car tyres, to increase the impact resistance (toughness) of plastics such as polystyrene and acrylonitrile butadiene styrene (ABS), and to make golf balls (Figure 5).
- Acrylonitrile butadiene styrene (ABS): computer monitors, printers and keyboards, drainpipes.
- Polycarbonate/acrylonitrile butadiene styrene (PC/ABS) blend: a stronger plastic which is used to make the interior and exterior parts of cars, and the unibody shells of mobile phones.
- Polyethylene/acrylonitrile butadiene styrene (PE/ABS) blend: a low-friction (slippery) material which is used in low-duty, dry bearings.

2.2.2 Plastics for more specialised applications[20]

There are very many different kinds of plastics employed, with particular features that render them suitable for more specialist purposes, for which the list below is indicative, though by no means exhaustive.

- Polyepoxide ('epoxy'): used as an adhesive, a potting agent for electrical components, and a matrix for composite materials which use hardeners, such as amine, amide, and boron trifluoride.
- Polymethyl methacrylate (PMMA) ('acrylic'): 'hard' contact lenses, toughened 'glass' materials (such as Perspex, Plexiglas, Oroglas), aglets (tubes at the ends of shoelaces), fluorescent light diffusers, rear light covers for vehicles; also in the 'acrylic paints' used commercially and by artists.
- Polytetrafluoroethylene (PTFE), or Teflon: to provide highly heat-resistant, low-friction coatings, as used in ('non-stick') frying pans, plumber's tape and water slides.
- Phenolics or phenol formaldehyde (PF): a thermosetting plastic, commonly known by the trade name 'Bakelite', that can be moulded by heat and pressure when mixed with a suitable filler (such as wood flour), or cast in its unfilled liquid form, or as foam (for example as known by the 'Oasis' trade name). The polymer is relatively heat resistant, provides a very effective fire resistance, and is used to make the insulating parts in electrical fixtures, in paper laminated products (such as 'Formica'), and in foams to provide thermal insulation. The material is not readily recyclable, since it is a thermoset.
- Melamine formaldehyde (MF): this is a member of the 'aminoplasts' polymers, and is used as an alternative to phenolics, for example to make less fragile versions of ceramic cups, plates and bowls for children to use. It can also be made to take a large range of different colours.
- Urea-formaldehyde (UF): another of the aminoplasts, which is also used as a multi-colourable alternative to phenolics, and is employed as a wood adhesive (for plywood, chipboard, hardboard) and to make housings for electrical switches.
- Polyetheretherketone (PEEK): among the more expensive polymers used commercially, this is a strong thermoplastic, which is resistant to heat and various chemicals, and is used in the fabrication of medical implants due to its biocompatibility, and to make mouldings for aerospace applications.
- Maleimide/bismaleimide: used to make high temperature composite materials of various kinds.
- Polyetherimide (PEI): an amorphous thermoplastic with characteristics similar to the related PEEK, and while PEI is cheaper than PEEK, its impact strength and usable temperature are both lower. Because of its adhesive properties and chemical stability, PEI became a popular bed material for FDM (fused deposition modelling) 3D printers. 'Ultem' is a family of PEI products manufactured by SABIC, as a result of its acquisition of the General Electric Plastics Division in 2007, and which were developed by Joseph G. Wirth in the early 1980s.
- Polyimide: a high temperature plastic that is used in such materials as Kapton tape.
- Silicones: these are heat resistant resins, used mainly as sealants but also for high temperature cooking utensils and as a base resin for industrial paints.

- Polysulfones: high temperature melt-processable resins used for membranes, filtration media, water heater dip tubes and other high temperature applications.
- Plastarch material: a heat-resistant thermoplastic made from modified corn starch, and which is biodegradable.
- Poly(lactic acid) or polylactic acid or polylactide (PLA) is a biodegradable and bioactive thermoplastic, aliphatic polyester that is obtained from renewable resources: in the USA and Canada, from corn starch; mostly in Asia, from cassava roots, chips or starch; and elsewhere in the world, from sugarcane.
- Furan resins: used in composites, cements, adhesives, coatings and casting/foundry resins, and prepared by the acid-catalysed polycondensation of furfuryl alcohol. Since the latter is produced from biomass such as corncobs or sugar cane bigasse, furfuryl alcohol is regarded as a green chemical feedstock.

3. Use of plastics by sector, and prognosis

As of 2015, 44.8% of all plastic resins were used[2] for packaging purposes, consisting of similar amounts each of LDPE, LLDPE, PP and PET, with another 18.8% being used by the building and construction industry, mainly in the form of PVC. The total primary production of plastics consumed by each sector is: packaging (146 Mt), building and construction (65 Mt), textiles (59 Mt), consumer and institutional products (42 Mt), transportation (27 Mt) and electrical/electronic (18 Mt). Not surprisingly, given the ‘once-through’ (single use) nature of most packaging, the estimated lifetime of plastics used in the packaging industry is under one year, with significantly longer lifetimes elsewhere: building and construction (35 years), industrial machinery (20 years), transportation (13 years), electrical/electronic (8 years), textiles (5 years) and consumer and institutional products (3 years)[2]. Of the 25 Mt of ‘additives; that are manufactured, 34% are used as plasticisers, 28% as fillers, 13% as flame retardants, 6% as antioxidants, 5% as impact modifiers, and another 5% as heat stabilisers. While a total 407 Mt of primary plastic was produced in 2015, 302 Mt of primary waste was generated[2]; however, the ratio of primary waste/production varies from sector to sector, and decreases according to the longer lifetime in use for the particular sector application: building and construction (20%), industrial machinery (33%), transportation (63%), electrical/electronic (72%), textiles (71%), consumer and institutional products (88%) and packaging (97%).

The annual production[2] of plastics in 1950 amounted to around 2 Mt, but this had risen to 407 Mt in 2015. By assuming a 4.5% compound annual growth rate (CAGR; as may be determined for the period[2] 2005–2015), the amount of plastics manufactured in 2018 can be estimated at 464 Mt. While this growth rate, if sustained, would yield a production rate of 1,900 Mt in 2050, it has been inferred, in a report[21] co-authored by the Ellen MacArthur Foundation, that by the year 2050, the annual production of plastics will amount to 1,124 Mt, which corresponds to a CAGR of 3% from that in 2015. However, it is further deduced[21] that this would nonetheless consume ‘20% of global annual oil production’ – up from 6% in 2014 – which is a sufficiently dramatic statistic to demand further elaboration.

Thus, from the report[21], we see that overall, in excess of 90% of the feedstock for the plastics industry is furnished by oil and gas, and on the basis of extensive literature research and modelling, it concludes that somewhere in the range of 4–8% (with 6% as the best estimate) of the world's output of oil (including natural gas liquids, NGLs), is consumed to manufacture plastics, for packaging plus all other uses: roughly half being used as chemical feedstocks and half to provide process production fuels[21]. This is equivalent in quantity to the annual global oil consumption of the aviation sector, and is in addition to the combined quantity of natural gas that is used to deliver feedstock and fuel. The conclusion that the consumption of oil (including NGLs) by the entire plastics sector will account for 20% of its total production by 2050 is based on an expected strong growth (an annual 3.5–3.8%) in plastics production being maintained, with oil production keeping in step with this. It is noteworthy that this is much faster than the expected annual growth in overall demand for oil, which amounts to just 0.5% (see ref. 21).

Furthermore, it is thought that to manufacture 1,124 Mt of plastics in 2050 will occupy 15% of the global carbon budget[21], which is set at a level to prevent the mean global temperature from rising beyond 1.5 °C greater than that in the pre-industrial period[22]. However, in view of the projected supply of oil and NGLs, and expected demand for them – mainly to provide energy, but for other applications too – it is debatable that a sufficient quantity will remain available to allow the plastics industry to grow to this large extent[23]. It is also probably unlikely that a matching quantity of bioplastics (Section 9.5) could be manufactured in order to substitute for this problematic commitment of fossil resources.

The report[21] also addressed the issue of environmental costs, which for all plastics amounts to an annual $75 billion, with the food sector accounting for 23% and the drinks industry 12% of the overall impact. However, it is argued elsewhere[24] that the use of plastics acts to preserve foodstuffs for longer than if they are sold loose, and reduces the amount of food waste, which is estimated at 1.3 billion tonnes per year[25], or one third of global food production. According to the Natural Resources Defense Council[26], just in the USA, producing food that goes to waste, occupies 25% of the nation's use of freshwater, and 4% of its oil consumption, while costing some $165 billion.

4. Plastic pollution

It has been reckoned that, the total mass of virgin plastics ever made amounts to 8.3 billion tonnes (see ref. 2), mainly derived from natural gas and crude oil, used as chemical feedstocks and fuel sources. Between 1950 and 2015, a total of 6.3 billion tonnes of primary and secondary (recycled) plastic waste was generated, of which around 9% has been recycled, and 12% incinerated, with the remaining 79% either being stored in landfills or having been released directly into the natural environment[2]. In the 'New Plastics Economy – Rethinking the Future of Plastics' report[21], the fate of plastic packaging waste is further quantified, concluding that approximately 40% of plastic packaging goes to landfill, while 32% leaks out of the collection system:

that is, either it is not collected at all, or it is collected but then illegally dumped or mismanaged, and ends up directly in the environment. The statistic has been given that at present rates of production and pollution, by 2050, there will be more plastic than fish in the sea (by mass)[21]. Only 28% of 'plastic packaging' was collected, of which half was incinerated to provide energy, while the other half was recycled. The report concluded that only 2% of the original 78 Mt was recycled into the high-value applications it originated from, allowing for processing losses, and that as a result of the material being used for lower value purposes, and a relatively low proportion being collected, a mere 5% of the original value was preserved[21]. It is thought that the current system may bear economic losses of perhaps $120 billion per year. (In the above report, it is estimated that 26% of total plastics use is for packaging, based on 78 Mt from a total of 299 Mt produced in 2013, albeit noting that this might be an underestimate[21]. Indeed, in another study[2], some 164 Mt of plastic was assigned to packaging, or 36% of the 407 Mt manufactured in 2015.)

Plastics are typically cheap to manufacture, and hence are used on a very large scale for many essential purposes of modern civilisation (Section 2). These materials are typically also chemically resistant, meaning that they degrade only slowly (Section 6.2), and hence billions of tonnes of plastics have accumulated in the environment. Land, waterways and oceans can become polluted by plastics, and living organisms, particularly those in ocean environments, can be harmed, for example by becoming entangled by plastic materials from packaging or discarded fishing lines, or they can ingest plastic waste. The latter may cause various health problems, either by direct physical action of the plastic items or particles, or potentially from the release of chemicals contained within the plastics that interfere with physiological processes: for example, by acting as endocrine disruptors, which disturb various hormonal mechanisms, both in animals and humans.

4.1 Types of plastic debris

On the basis of size[27], plastic pollution can be differentiated as macroplastic, mesoplastic, and microplastic, although the term megaplastic[27] has also been used, and there is speculation as to the likely quantities of nanoplastic[28] that might exist, particularly in marine environments. Although it is normal practice in the chemical and physical sciences to use the terms, micro-, meso-, and macro-, to characterise particular structural components by size range[29], for example the different pores in microporous (nanoporous) solids (such as activated carbons or zeolites), or in soil science, where the terms clay, silt and sand are used to define mineral particles in soil according to their size rather than their chemical composition[30], there is as yet no universally agreed such set of scales for plastic pollution. At present, all plastic items of 5 mm in dimension, or greater, tend to be classed as macro-, and anything smaller than this as micro-. Among the larger-sized (macro) plastic debris are plastic chairs, shoes, parts of vehicles – cars, ships and planes – buoys, footballs, plastic shopping bags, and many other commonly used items, and the 'ghost net', which is a fishing net that has been lost or abandoned, so that it drifts along with the ocean tides and

Figure 6 *Plastic pollution on Henderson Island. Credit: American, https://upload.wikimedia.org/wikipedia/commons/4/4e/Hendersonm%C3%BCll.jpg.*

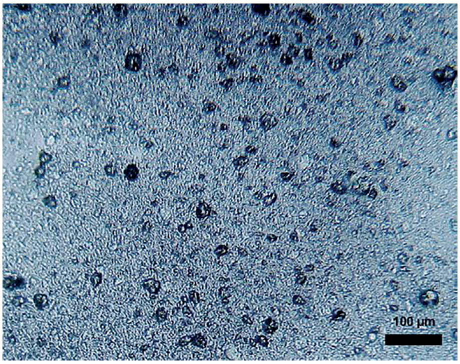

Figure 7 *Polyethylene based microspherules in toothpaste. Credit: Dantor, https://upload.wikimedia.org/wikipedia/commons/a/a9/Mikroplastasarp.jpg.*

currents, and traps sea creatures and additional macrodebris, eventually becoming fully laden, mainly with other plastic objects. Such ghost nets have been reported to accumulate to masses of perhaps 6 tonnes, by when they are too large, and too heavy to be recovered from the ocean[27]. The greatest densities of the world's plastic pollution have accumulated around water fronts and urban centres in the Northern Hemisphere, although such depositions may also collect off the coasts, and wash onto the beaches of particular islands (Figure 6) as a result of the directional flow of currents (gyres) which transport the debris. A further classification applied to plastic pollution (debris) is as being either primary or secondary: as collected, primary plastics are still in their original form, such as cigarette butts, bottle caps, nurdles (1–5 mm diameter, primary plastic pellets, that are moulded into plastic items) and microbeads (5 µm–1 mm in diameter, which are used in personal care products [Figure 7], and for industrial abrasion purposes)[31]; secondary plastics are smaller items that have been formed by the disintegration of primary plastics[32].

4.1.1 Microplastics (microdebris)

The US National Oceanic and Atmospheric Administration categorises microplastics as being less than 5 mm in diameter[33]. Primary microplastics are plastic particles that were originally manufactured at those sizes in which they are encountered in the environment. Some primary microplastics are deliberately designed as 'scrubbers', for use in exfoliating hand cleansers and facial scrubs, and have increasingly been used as substitutes for traditional materials, such as ground almonds, oatmeal and pumice[31]. They have also found application in industrial processes, where acrylic, melamine, or polyester microplastic scrubbers are air-blasted at machinery, engines and boat hulls in order to scour rust and paint from them. This causes the particles to become eroded with repeated use, until they require disposal, by when they are not only reduced considerably from their original size, but may have acquired toxic heavy metals such as cadmium, chromium, and lead[34]. Clothes – fleece, nylon, polyester, and Spandex – provide another significant source of primary microplastics, in the form of microfibres, when they are washed[35].

Primary microplastics, in the form of lentil-sized pellets (nurdles), are processed to make new plastic items. They range in size from 1–5 mm in diameter[36], and an approximate annual 60 billion pounds (27 Mt) of nurdles is manufactured in the USA[37]. One pound of pelletised HDPE contains around 22,000 nurdles[37] (meaning that each nurdle weighs roughly 20 mg). On account of their small size, they often find their way into ocean waters, and onto beaches (Figure 8) *via* rivers and streams[27,31], sometimes due to accidental spillages (Figure 9) that may occur during transportation by land or sea, by their being used inappropriately for packaging purposes, from land based sources, or by direct outflow from processing plants.

Rehse *et al*. have stressed[38] that the results often vary between different studies, due to limitations of current sampling and evaluation procedures, and that the use of alternative reference units, makes it difficult to compare such differently obtained results directly. Thus, data are often reported as either the number (or mass) of microplastic particles per unit area (*e.g.* m^2) or per volume (*e.g.* m^3). Thus, ranges of microplasic mass concentrations have been obtained: 10^{-3}–10^{-1} mg m^{-3} for rivers, and 10^{-3}–10^{-1} mg m^{-2} for lakes[39,40]. In terms of particle numbers, up to 10 particles m^{-3} have been determined in surface water samples from both rivers and lakes[39–41]. The most heavily polluted rivers appear to be in Asia, with up to 1,000

Figure 8 *Nurdles on a beach in southwest France, in 2011. Credit: Maldeseine, https://upload.wikimedia.org/wikipedia/commons/9/9d/Granul%C3%A9s_plastiques_industriels_sur_une_plage_de_la_c%C3%B4te_Aquitaine.JPG.*

Figure 9 *A handful of nurdles, spilled from a train in Pineville, Louisiana, USA. Credit: gentlemanrook, https://upload.wikimedia.org/wikipedia/commons/f/fd/Nurdles_01_gentlemanrook.jpg.*

microplastic particles m^{-3} (which corresponds to 1,000 mg of plastic m^{-3}) in the Yangtze River[42,43].

When samples were taken from waters off Sweden, using an 80 µm mesh, concentrations in the range 150–2,400 microplastic particles m^{-3} were determined, while the concentration was found to be 102,000 particles m^{-3} in a harbour adjacent to a plastic manufacturing plant[44]. As present in the oceans, microplastics can act as a sink for hydrophobic, persistent, bio-accumulating toxins such as dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyls (PCBs), the release of which, following ingestion, might cause adverse health effects. However, the likelihood of microplastics acting as vectors for an enhanced uptake of such hydrophobic organic pollutants has been challenged[45–47], and it is possible that microplastics might even act to decrease the short term effects of contaminants[38,48]. Nurdles have been detected in the digestive tracts of various marine creatures, from where they might potentially deliver both intrinsic plastic additives (such as phthalates, which are used as plasticisers) and hydrophobic pollutants that they have absorbed from seawater: thus, it was found that nurdles taken from waters off the coast of Japan had accumulated PCBs and DDE in concentrations of up to one million times greater than those in the surrounding seawater[49]. On account of their small size, microplastics may also be taken up by filter-feeding organisms[27]. Secondary microplastics are formed when larger plastic items are degraded into smaller fragments by mechanical/physical action, photodegradation, and a range of other processes, and hence, plastic pollution that initially corresponded to macrodebris, can be broken down into a larger number of smaller (microdebris) particles[38,50]. Most microplastics in the marine environment fall into this secondary category[51–53], as is attested to by the fact that their particles most often have uneven shapes[54]. Although the smallest microparticles that have apparently been detected in the oceans have a diameter of 1.6 µm (1,600 nm), it is thought that further fragmentation could occur to form nanoplastics[34].

The relation between mass, particle size, number of particles, and total surface area can be illustrated as follows, with reference to Table 2. A 1 kg cube, made of plastic with a density of 1, obviously consists of a single particle, with an edge length of

Table 2 *Idealised connection between particle size, number of particles, and total surface area for a cube that is increasingly divided into smaller cubes*

Edge length	Diameter	No. of particles	Particle area (m^2)	Total particle area (m^2)
10 cm	0.173 m	1	0.06	0.06
1 cm	1.73 cm	10^3	6×10^{-4}	0.60
1 mm	1.73 mm	10^6	6×10^{-6}	6
1 µm	1.73 µm	10^{15}	6×10^{-12}	6×10^3
100 nm	173 nm	10^{18}	6×10^{-14}	6×10^4
10 nm	17.3 nm	10^{21}	6×10^{-16}	6×10^5
1 nm	1.73 nm	10^{24}	6×10^{-18}	6×10^6

10 cm (0.1 m), corresponding to a space diagonal (diameter of circumscribed sphere) of 17.3 cm (0.173 m), and a total surface area of 0.06 m^2. However, if this is broken down into 1 cm cubed pieces, there are now 1,000 particles, each of surface area 0.0006 m^2, but since there are 1,000 of them, the sum of their surface areas is 0.6 m^2. It can be seen that as the degree of fragmentation progresses, increasing numbers of particles of ever smaller sizes are created, but their total surface area rises accordingly. Hence, the creation of nanoplastics has the potential to increase both their environmental uptake and ingestion by living creatures, being far smaller than the initial macro- and meso-sized forms from which they were created, and in far greater number, hence increasing the overall activity of the plastics on a statistical basis. Probably more important, however, is the dramatically enlarged surface area that is exposed *via* the fragmentation process, and increased surface/volume ratio of individual particles, factors which are likely to result in their greater biological activity, especially if surface electric charges develop, which have been shown to enhance particle–cell interactions[55]. The increased surface area also means that the plastic particles have a greater capacity to absorb toxic chemicals from the environment, particularly when they are present in the oceans, which it is feared might be passed on into the tissues of animals that ingest them although this issue is contentious[38,45–48]. Clearly, the above scheme is highly simplistic, since the actual particles are broken down into a far more complex distribution of shapes than sequentially smaller, simple cubes, but it does broadly illustrate the main features of the fragmentation process. Indeed, more irregular particle forms are likely to present yet greater surface areas, and sharper, jagged particles, of < 1.5 μm dimension might penetrate tissues more readily[56].

The ubiquitous nature of microplastic pollution in the oceans was strongly indicated in a 2004 study, which further determined that both domestic and industrially derived plastic pellets were being fragmented into secondary particles, some with a smaller diameter than a human hair (*ca* 70 μm)[57]. It was concluded that the microdebris floats in the ocean waters, as a kind of thin soup[58]. More recently, results were obtained[59] which indicated that the concentration of microfibres (Figure 10) was greater by four orders of magnitude per unit volume in deep-sea sediments, than in heavily contaminated surface water gyres (1.1×10^{-4} per 50 mL); and it was estimated[59]

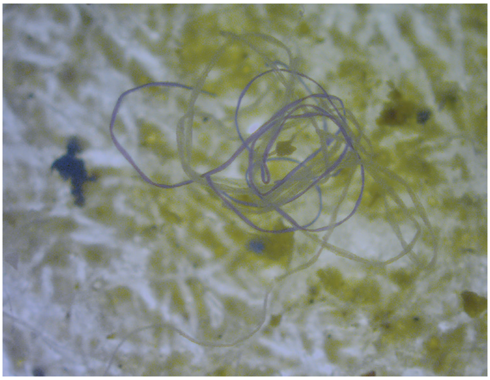

***Figure 10** Microplastic fibres identified in the marine environment. Credit: M.Danny25, https://upload.wikimedia.org/wikipedia/commons/0/0d/Snap-40.jpg.*

that there might be four billion microfibres per km^2 in the Indian Ocean seamount sediment (this would appear to correspond to a sediment depth of 5 cm). Hence, sediments might provide significant repositories for microplastic particles, especially given the *ca* 300 million km^2 total area of the global deep sea habitat[59].

4.1.2 Primary microplastics from the abrasion of textiles and tyres

It has been estimated that, in Denmark, an annual 5,500–14,000 tonnes of microplastics are released into the environment, and that secondary microplastics, *e.g.* from the tyres of road vehicles, and from footwear, contribute by two orders of magnitude more than primary microplastics. The study did not include the levels of microplastics which result from the degradation of larger plastic items in the environment[60]. That this may be the case on the global scale, is supported by a recent report from the International Union for Conservation of Nature and Natural Resources (IUCN)[61], which concluded that up to almost a third of the 'plastic soup' that exists in the world's oceans may be due to microplastics, and that, for many industrialised nations, this accounts for a greater amount of plastic pollution than the larger, more visible, (macroplastic) items of marine debris. Similarly to the Danish study[60], the report[61] made an analysis of microplastics, specifically resulting from: the abrasion of synthetic textiles during laundry; the abrasion of tyres while driving; city dust from spills, weathering and abrasion; weathering and abrasion of road markings by vehicles; weathering, application and maintenance of marine coatings; loss during use from personal care products; and manufacturing, transport and recycling of plastic pellets[61]. On top of some 8.0 Mt of plastic waste entering the oceans, 1.5 Mt (0.8–2.5 Mt) of microplastics was reckoned to be released into the oceans annually (the 8.0 Mt figure for plastic waste is within the 4.8–12.7 Mt range determined by other workers[62]), around two-thirds of which originates from synthetic textiles, when they are washed (35%), and from the abrasion of tyres while vehicles are driven (28%) (see ref. 61). This suggests that *ca* 0.53 Mt of microfibres and 0.42 Mt of tyre dust enter the oceans annually. (The IUCN estimate[61] for tyre dust rises from 28% [for synthetic rubber alone] to 46%, and hence to 0.69 Mt as an annual contribution of microplastics to the oceans, if their natural rubber content is also considered in the reckoning.) Kole *et al*. concluded[63] that in 2013, a total of 3.4 Mt of tyre dust was produced globally, although it is not clear how much of this might have ended up in the oceans; similarly, from a study by Orb Media, it is claimed that[64] 'an estimated 1 million tons of these tiny microfibres are discharged into wastewater every year, where more than half evade treatment and escape into the environment', which indicates that up to 0.5 Mt or so might enter the ocean – depending on the degree of interception by the intervening environment. The authors of the report[61] welcome calls to ban the use of microbeads in cosmetics, but note that only 2% of primary microplastics arise in this way, hence limiting the true impacts of such a ban. Kole *et al*. further concluded[63] that emissions from the wear and tear of tyres (which generate 10–60 g of dust per 100 km driven, depending on vehicle weight – *i.e.* car, bus or truck) (100%) are far larger than those from airplane tyres (2%), artificial turf (12–50%), brake wear (8%) or road markings (5%), and that some

5–10% of the total amount of plastic waste in the oceans arises from the abrasion of car tyres[63]. Tyre abrasion was reckoned[63] to account for 3–7% of airborne particulate matter (PM2.5), which is a contributor to the burden of global air pollution: the latter was assessed by the World Health Organization (WHO) to have caused three million deaths in 2012. Although research is currently lacking to assess fully the health risks from such material entering the food chain, it is concluded that 'tyre wear and tear is a stealthy source of microplastics in our environment'[63]. From a study by Timmers and Achten[65], a different distribution of vehicle particle origins was reported, which suggests that the particulate emissions from brakes and road surfaces may actually be larger than that from tyre abrasion, and that 90% of the emissions from a vehicle are from these non-exhaust sources. This is placed in the context of the reduction in particulate emissions that might be expected from electric vehicles (EV) as compared with diesel or petrol fuelled cars, and that if the greater weight of an EV is taken into account, the reduction is probably only in the range 1–3% (see ref. 65).

4.2 Removal of microplastics by wastewater treatment plants

Wastewater is filtered in treatment plants to form an effluent, and while both primary and secondary microplastics have been identified in these plants, it has been found that the majority of them are removed during the primary treatment, where solid skimming and sludge settling are used[66]. Nonetheless, due to the very large volumes of water being treated, the final effluents can still serve to discharge significant amounts of microplastics into the environment. According to one study, although > 98% of the microplastics were removed by a wastewater treatment plant (WWTP), nonetheless some 65 million of them passed on through, and into the outlet waters[67]. It has been estimated that in the USA, WWTPs are responsible for the discharge of eight trillion microbeads every day into aquatic habitats, thus contributing a significant source of microplastics[68]. An investigation was made[69] of different wastewater treatment technologies which showed that by using a membrane bioreactor (MBR) for treating primary effluent, around 99.9% of the microplastics could be removed (reducing their concentration from 6.9 to 0.005 microparticles per litre). Thus, through an appropriate choice of treatment technology, it is possible to curb significantly the level of microplastic pollution that is discharged from wastewater treatment plants into the aquatic environments[69].

5. Ingestion of microplastics by organisms

Although most attention to date has been towards the more visible effects of larger plastic items, fuelled by harrowing images of marine animals becoming entangled, sometimes fatally so, by plastic items such as six-pack rings and plastic bags, or being starved and generally debilitated by ingested plastic, mistaken for food, microplastics, which are less apparent due to their small size of less than 5 mm, can nonetheless cause serious problems for a very broad range of species. Indeed, the ingestion of microplastics is widespread: thus, microplastics have been found embedded in the gastrointestinal tracts (GIT) of various species of annelid, such as deposit-feeding

Lugworms (*Arenicola marina*)[70] (Figure 11) in perch larva (Figure 12) and to be present in both the digestive and respiratory tracts of crustaceans, such as the Shore Crab (*Carcinus maenas*)[71] (Figure 13). Benthic sea cucumbers are bottom feeders (non-selective scavengers that feed on debris on the ocean floor), and accordingly ingest large amounts of sediment. However, it was discovered that the species, *Thyonella gemmate*, *Holothuria floridana*, *H. grisea* and *Cucumaria frondosa*, appeared to ingest plastic particles, selectively, over and above the plastic to sand grain ratios from each sediment treatment – up to a factor of 20-fold in the case of PVC fragments and up to138-fold more for fragments of nylon line. This appears to be curious behaviour, and has promoted the suggestion that perhaps all non-selective feeders might show such a preference for microplastics[72]. However, we may note a paper[73] published in *Science*, which prompted wide media coverage in its claim that young fish preferred eating plastic particles to natural food, and when interviewed by the BBC shortly after its publication, the lead author (from Uppsala University) said that for young fish, plastic could be compared to 'unhealthy fast food for teenagers'. The paper has since been retracted, and the following statement was issued by the journal[74]: '*Science* has been informed that the University of Uppsala has completed its investigation into the study by Lönnstedt and Eklöv, published in *Science* on 3 June 2016 and retracted on 3 May 2017. (The retraction ran online on 3 May and in print on 26 May 2017.) The investigation has found that both authors were guilty of

Figure 11 *The Lugworm* (Arenicola marina). *Credit: 4028mdk09, https://upload.wikimedia.org/wikipedia/commons/e/e7/Arenicola_marina_2010.JPG.*

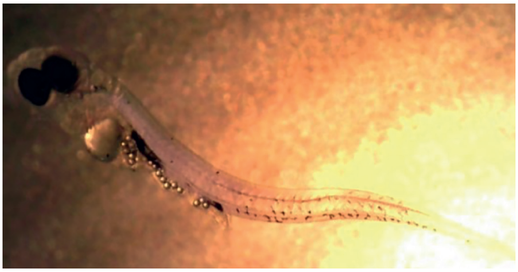

Figure 12 *Microplastic particles ingested by a perch larva. Credit: Oona M. Lönnstedt, https://upload.wikimedia.org/wikipedia/commons/5/5c/Microplastic_particles_influence_in_Perch_Larval.png.*

Figure 13 *A young, Shore Crab* (Carcinus maenas). *Credit: Luis Miguel Bugallo Sánchez, https://upload.wikimedia.org/wikipedia/commons/6/67/Crab_Cangrexo_66eue.jpg.*

research misconduct; that both authors violated the regulations on ethical approval for animal experimentation; and that Lönnstedt fabricated experimental results reported in the paper.'

Nonetheless, the ingestion of microplastics in the form of beads (1.7–30.6 µm) by zooplankton has been demonstrated, which also stick to the appendages and exoskeletons of these creatures[75], and the contamination is passed through to their faecal matter. It is thought that zooplankton, along with other susceptible marine wildlife, are attracted to consume marine-seasoned plastic debris because the latter become coated with a layer of algae, which when they decompose release dimethylsulphide (DMS) – a 'keystone infochemical' odorant for natural trophic interactions: in other words, it 'smells' like food. By using Procellariiform seabirds as a model taxonomic group, a positive correlation was found between the frequency of plastic ingestion and responsiveness to DMS[76]. (The birds eat krill, which feeds from the algae, and are hence drawn, in a Pavlov's dog fashion, to the scent of DMS, which they associate with finding food. Hence, when plastic becomes coated with DMS-emitting algae, they are drawn into an 'olfactory trap', and eat pieces of plastic, as they would krill.) Some species of sea turtles often mistake floating plastic bags for jelly fish, which they normally consume, and consequently suffer from obstruction of the oesophagus which can lead to their death[77]. Large quantities of plastics have also been found in the stomachs of beached whales[77]. Differential responses[78] have been reported from six small-polyp stony coral species from the genera *Acropora*, *Pocillopora*, and *Porites* on exposure, over a 4 week period, to polyethylene particles (37–163 µm), at a concentration of *ca* 4,000 particles L^{-1}. Cleaning mechanisms, by direct interaction, and mucus production, were observed, but feeding interactions, such as interaction with mesenterial filaments, ingestion, and egestion, also occurred. Bleaching and tissue necrosis were found in five of the six species that were studied. It is thought that further research is necessary to determine the effects of microplastics on the growth, reproduction, and survival of stony corals, at realistic concentrations, and to better comprehend the resilience capacities of coral reef ecosystems[78].

The lantern fish is the most common of the mesopelagic fish, and lives in the central ocean gyres, which comprise a large system of rotating ocean currents. The plastics that are ingested by lantern fish become incorporated in the food chain, because they are a principal source of food for tuna and swordfish, which are popular for human consumption. In a study[79] made by the Scripps Institution of Oceanography, it was determined that the average content of plastic was 9.2% in the stomachs of 141 mesopelagic fish (which included 27 different species), and that, in the North Pacific Ocean, fish were consuming between 12,000 and 24,000 tons of plastic debris per year. Such a large consumption of plastic, rather than food, will further impair the nutrition of the fish, and so their nutritional value across subsequent trophic levels[79].

A comprehensive and recent review was published of the ingestion and effects of microplastics on mesopelagic fish[80]. Following an earlier study[81] that showed the presence of high levels of persistent organic pollutants – PCBs (used as dielectric fluid) and polybrominated diphenyl ethers (PBDEs, used as flame retardants) – in crustaceans living at ocean depths of 7 km (New Hebrides Trench) and 11 km (Mariana Trench)[81], researchers at Newcastle University have also identified[82] plastic fibres in the bodies of these creatures. The proportion of creatures that had ingested plastic was measured at 50% in the New Hebrides Trench, and 100% at the bottom of the Mariana Trench. Among the different microplastics identified were semi-synthetic cellulosic fibres, such as are used in textiles, mainly for clothing (Rayon, Lyocell and Ramie), nylon, polyethylene, polyamide, and unspecified polyvinyl polymers, similar to PVA or PVC. The deep oceans have often been regarded as pristine environments, free from contamination, but these results show this is far from being the case. Debris 'raining down' from higher levels in the ocean will accumulate at depth, from which animals that live there will tend to bioaccumulate toxic materials, since they are dependent on it as their source of food[82].

5.1 Seabirds

Seabirds are also affected by plastic, and it was estimated that, on average, seagulls living around the North Sea had 30 pieces of plastic in their stomachs[83], the reason being that they perceive floating debris as prey, and thus ingest it, or feed it to their nestlings[84]. They may also eat other creatures that have ingested plastic debris, which is hence passed on from prey to predator. The presence of plastic in the digestive system, may cause physical damage and obstruction, or a false sense of satiation, leading to malnutrition, starvation, and death. Floating pieces of plastic may discharge plasticisers into the tissues of birds that eat them, where they can become concentrated, thus impairing the creature's reproductive ability, immune system, and hormone balance[85]. Pieces of plastic may also accumulate in the bird's gut, resulting in starvation, and the corpses of birds may be seen with plastic remaining where the stomach once was; in some cases, pieces of plastic still remain after the corpse has decayed[86]. It is possible that plastic debris is present in the bodies of 90% of seabirds[87], a figure that is predicted to rise to 99% by 2050[87].

5.2 Humans and animals

As noted in Section 3, various additives are employed in the production of plastics, *e.g.* phthalate plasticizers, or polybrominated biphenyls (BPBs) – used as flame retardants, which might present harmful biological effects such as carcinogenicity or endocrine disruption. By means of biomonitoring, it was established that, in the USA, 95% of adults had detectable levels of bisphenol-A (BPA) in their urine. Exposure to BPA, and di-(2-ethylhexyl)phthalate (DEHP), which are endocrine disrupting agents, has been correlated with disturbances in fertility, reproduction, sexual maturation, and other adverse health effects[88]. While certain other phthalates have been linked to similar biological effects, the harmful nature of phthalates in general is much debated, and the complexity of the matter is demonstrated by the fact that, in mature animals, each type of phthalate compound exhibits a different toxicity profile[89]. Humans can be exposed to these, and many other chemicals, simultaneously, through inhalation, ingestion, or absorption through the skin or eye. Although the typical levels of daily exposure are within the accepted safety limits, to evaluate fully the effects of low doses of these substances on humans requires far more research[88]. Certain additives used in plastic production may cause dermatitis through contact with human skin[88,89]. When animals are exposed to plasticisers, they may experience developmental defects: for example, when sheep were exposed to bisphenol A, at a prenatal stage, lower birth weights resulted, and in studies on tadpoles, it was found that the distance between the eyes decreased. In frogs, a shortening in body length by such exposure, was noted, and in different species of fish, egg hatching can be inhibited, and body weight, tail length, and body length may all be diminished[85].

Food supplies might be affected through contamination of animals that are subsequently eaten by humans[45,46]. Since at least one-fifth of the animal protein intake for 20% of the world's population is derived from fish[90], the prospect that microplastics might be ingested by fish and crustaceans, and then transferred to humans at the end of the food chain should be considered. The consumption of plastic by lantern fish, which are a food source for other fish, such as tuna and swordfish has already been noted[79]. Although it is known that plastic particles may be able to absorb and concentrate synthetic organic compounds such as persistent organic pollutants (POPs) from seawater, by surface adsorption[49], evidence for the subsequent transfer of these materials to organisms is not definitive; however, the absorption of microplastics by trophic transfer to marine top predators has recently been demonstrated, which presents, therefore, a potential route for microplastic ingestion by animals whose feeding ecology involves the consumption of whole prey, including humans[91]. Results from recent studies suggest that microplastics are less important for the bioaccumulation of hydrophobic organic pollutants (HOCs) in the oceans[45,46], than is the flux of HOCs bioaccumulated from natural prey. It is thought, therefore, that the degree of exposure to HOCs in the marine environment is unlikely to be made worse through the ingestion of microplastics. It is considered, however, that it might be appropriate to regard microplastics themselves as POPs[46]. Field evidence has also been presented for the transfer of microplastics along a terrestrial food chain: from soil, to earthworms, to chickens[92].

5.3 Microplastics in drinking water

Of 159 samples of tap water collected from six regions on five continents, 83% were found to contain plastic particles. Samples taken in the USA showed the highest level of plastic contamination, at 94%, followed by Lebanon and India. Europe fared the best, where from 18 samples taken in seven countries a contamination rate of 72% was scored. The results suggest that people may be ingesting between 3,000 and 4,000 plastic microparticles every year from tap water[93]. Most of the particles found were fibres with a length range of 0.1–5 mm, and from 0–57 particles were detected per litre of water, averaging at 4.34 particles per litre. Any effects of the plastic ingestion on human health are as yet unknown, but it is thought that if the drinking water is also contaminated with nanoparticle pollutants, adverse consequences are possible. The potential ingestion of microplastics by humans has so far been considered to occur *via* the food chain, *i.e.* by eating other creatures that have consumed plastic particles, but this study raises the prospect that humans may ingest them directly from water and other beverages. It is not yet clear how, or if, this kind of pollution could be transferred between the 'commons' of air, water, and soil, but a general trend has been noted that if any of them becomes contaminated 'it gets in everything'[64].

5.4 Actual evidence for toxic effects from plastic ingestion by humans

Wright and Kelly[94] and also Galloway[55], have stressed that current understanding of the degree to which the human population is contaminated by environmental sources of microplastics is in its infancy. Although there are concerns that the ingestion of micro/nano-plastics might cause adverse health effects in humans, as yet there is little firm evidence that this is the case[94]. However, since microplastics have been detected in foodstuffs, such as seafood[95–97], sugar[98], beer[99], salt[100], and honey[98], and also in drinking water[64,93], the potential for human exposure is real. The presence of microplastics has been demonstrated in air, which provides both a potential route to exposure through inhalation[101,102], and an airborne source of food contamination *via* deposition from the atmosphere[103]; however, the actual uptake of microplastics and any associated toxic chemicals into human tissue *via* either of these routes is presently unknown. It is thought that the application of sludge byproducts from wastewater treatment plants, which contain synthetic fibres from clothes[104], might also provide an airborne source of microplastics, as driven by the wind, in addition to plastic particles arising from the disintegration of polyethylene sheets, as are used on farms, and synthetic fibres that are taken up by the wind when clothes are dried in the open air[105]. In regard to occupational exposure to microfibres, it has been noted that nylon workers do not suffer an increased incidence of cancer, although a greater level of respiratory irritation was recorded[106]. In samples of both non-neoplastic and malignant lung tissue taken in biopsies from patients with different types of lung cancer, the presence of cellulosic and plastic microfibres was noted[107]; however, their biopersistent nature was indicated by the fact that they had undergone very little degradation under physiological conditions. It has been speculated[94], on the basis of existing knowledge from related fields, that plastic particles which have entered the body through ingestion or inhalation, may pose dangers from chemical, or microbiological effects, and that an accumulation of microplastics could occur as a result of chronic exposure, causing localised toxicity by inducing or exacerbating an immune response. If, over time, additives, monomers, or adsorbed toxic environmental pollutants were released, chemical toxicity might result. Wright and Kelly have identified[94] a set of 'knowledge gaps', where research efforts need to be targeted to comprehend the realities regarding the toxicity/toxicology of microplastics:

1. What are the overall exposure concentrations from dietary and airborne sources?
2. What proportion of microparticle exposure do microplastic comprise?

3. Do different biological responses to microplastics manifest due to their unique chemical compositions/properties?
4. What effect does the interchangeable gastric environment/lung lining fluid have on the surface charge and chemistry, and therefore handling of microplastics?
5. What is the composition of the protein corona on microplastics?
6. Is there evidence of microplastic uptake in humans?
7. Are microplastics able to accumulate in the body? Do they become lodged or are they engulfed by cells?
8. If taken up by cells, what is the cellular mechanism of uptake? Does subcellular localisation or translocation occur?
9. If subcellular location occurs, does this 'hijack' the route for endogenous microparticle uptake or compromise immune homeostasis?
10. Does dissemination and/or elimination occur? Are there target secondary organs?
11. Are accumulative effects the same as those observed in occupational exposures?
12. Are larger particles a greater issue for the gastrointestinal tract (GIT) due to the process of persorption?
13. What is the toxicological response to biopersistent microplastics? Do inflammatory responses mimic those observed in response to plastic prosthetics wear debris?
14. Do size and shape influence toxicity? Does this depend on the point of entry, *e.g.* are plastic microfibres of greater concern for the lung than the GIT?
15. Do polymer type and hydrophobicity influence toxicity?
16. Does surface charge of microplastics affect toxicity and does this vary with time in the environment (and therefore exposure to UV)?
17. Once uptaken, can microplastics deliver their chemical burden and does this cause localised toxicity?
18. What will the addition of the novel hard surface of microplastics, for which specific microbes and biomolecules have an affinity for, have on the microbiome?

6. Environmental consequences of plastic pollution

6.1 Entanglement

Some of the most emotive images of environmental pollution are those featuring animals that have become helplessly entangled in plastic debris (Figure 14). Many marine creatures, including sea turtles, seals, sea lions, seabirds, fish, whales and dolphins, become encircled or ensnared by the debris and end up suffocating or drowning; or they may die as a result of starvation, or being unable to escape from predators[27]. Abandoned fishing equipment – such as ghost nets, ropes and lines – is often made from highly durable, tough and buoyant materials such as nylon, rendering them especially dangerous to animals (Figure 14); nets can also drag along the seabed, damaging coral reefs in the process[108]. Becoming entangled in plastic may also cause severe lacerations, ulcers, and infections; and if the animal continues to grow in size, the material can cut into its flesh. Every year, more than 400,000 marine mammals are thought to die due to pollution of the oceans by plastic[77].

The distribution of plastic debris is determined by a range of influences, such as wind and ocean currents, coastline geography, urban areas, and trade routes, and is accordingly highly variable. Plastics are more likely to be found in coastal locations that are very populous, and in regions such as the Mediterranean, that are enclosed[109]. Approximately half of all plastic is buoyant[109] (*i.e.* it floats), and in consequence, may serve to transport organisms to remote locations that are not their native environments, thereby endangering marine biodiversity, globally, if aggressive and invasive alien species are introduced, which may cause disruptions to local ecosystems[108]. When they become fouled by organisms, initially buoyant plastic items can be caused to sink to the sea floor, where they may impact on species which dwell in sediments. The ingestion of microplastics has been observed to affect the buoyancy of certain autotrophs (organisms that produce complex organic compounds [such as carbohydrates, fats, and proteins] from simple substances present in their surroundings, generally using energy from light [photosynthesis] or inorganic chemical reactions [chemosynthesis][110]) by interrupting photosynthesis and consequently changing the levels of gases within them[111].

***Figure 14** Sea turtle entangled in a ghost net. Credit: Doug Helton, NOAA/NOS/ORR/ERD, https://upload.wikimedia.org/wikipedia/commons/0/08/Sea_turtle_entangled_in_a_ghost_net.jpg.*

6.2 Decomposition of plastics

Plastics tend to be exceptionally stable and durable, which is why they have gained their popularity and wide application in society; however, these same qualities render them persistent in the environment, and resistant to decomposition when it is desired to dispose of them[112]. Under environmental conditions, plastics may undergo degradation by four principal mechanisms: photodegradation, thermooxidative degradation, hydrolysis and biodegradation by microbes[50]. Photodegradation by sunlight is generally the initial event, which primes the material for subsequent thermooxidative degradation[50,113]. As a result of these processes, the plastic becomes brittle and steadily dissociates into increasingly smaller fragments: finally, down to the molecular level, such that they can be metabolised by microbes[50,114], which either incorporate the carbon atoms from the polymer chains into biomolecules, or oxidise them to CO_2 (see refs 50 and 115). The overall process of decomposition is very slow, however; an estimated 50 years for a foam plastic cup, 400 years for a plastic drinking cup, 450 years for a disposable nappy, and 600 years for a fishing line[86]. The persistence of plastic in the oceans is enhanced by the limited availability of oxygen, and by the cooling effect of the water; also, rates of hydrolysis are too low to provide an effective route for the decomposition of most polymer components of plastic debris[50].

To consign plastic waste to landfill involves rendering unavailable land that might otherwise be more productively used, such as for agriculture[116], and in combination with the fact that most plastics degrade but slowly, especially in landfill environments, which are practically anaerobic (and cannot provide a necessary concentration of oxygen to support active thermooxidative degradation), the land is necessarily thus occupied for a longer term. When such degradation does occur, the plastic may discharge a host of secondary pollutants, which include volatile organic species (VOCs), such as benzene, toluene, xylenes, ethylbenzene and trimethylbenzene isomers, either as gaseous components, or *via* leachate[117], along with various other substances, including BPA[117–119], with the risk of groundwater contamination. In addition to its acknowledged role as an endocrine disruptor, BPA has been demonstrated to promote the production of hydrogen sulfide by sulfate-reducing bacteria that are present in soil[119].

6.3 Marine debris (marine litter)

Marine litter has been defined as follows[120]: ‘any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Marine litter consists of items that have been made or used by people, and deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; accidentally lost, including material lost at sea in bad weather (fishing gear, cargo); or deliberately left by people on beaches and shores.’ The potential economic losses that can arise from marine litter have been highlighted by the European Commission: as a result of tourism, shipping and fishing, with particular impacts on coastal communities, the costs of cleaning coasts and beaches across the EU, were reckoned at nearly €630 million per year, along with a loss of €60 million to the fishing industry[121].

A number of different categories of marine debris have been identified[120]:

- Plastics – moulded, soft foam; nets, ropes, buoys, monofilament lines and other items related to fishing; cigarette butts, lighters and other items related to smoking; and microplastic particles.
- Metal items – cans, for drinks and aerosols; aluminium foil; and disposable barbeques.
- Glass-bottles, buoys, light bulbs, and fluorescent bulbs.
- Processed timber – pallets, crates and particle-boarding.
- Paper and cardboard – cartons, cups and bags.
- Rubber – tyres, gloves and balloons.
- Textiles – item of clothing, furnishings, towels and shoes.

- Sewage related debris (SRD) – cotton bud sticks, condoms, sanitary products and nappies.

Although just 10% of all municipal waste is produced[122] in the form of plastics, they nonetheless comprise 50–80% of shoreline debris items, the quantity of which is anticipated to increase relentlessly[123]. Due to their abundance, longevity, and that they may traverse large distances of ocean, plastics pose a significant risk to the marine environment. It has been estimated that 20–40% of marine debris (by mass) emanates from accidental or deliberate discharges at sea[124], which is higher than the commonly expressed, though largely unsupported, attribution of 20% to sea-based sources and 80% to land-based sources, although these relative contributions are known to vary from area to area[124].

6.3.1 Land-based sources of marine debris[120]

The high proportion of marine debris that has land-based origins, arises from a range of different sources, and behaviours, as is indicated by the following list.

- Public littering – according to the 2009 UK Beachwatch survey[125], littering by members of the public was responsible for 42% of all the debris found; thus, many different kinds of item are discarded, either accidentally or deliberately, at the beach, coast or into rivers, thereby subsequently entering the marine environment.
- Poor waste management practices – debris from waste collection, transportation and disposal sites, that is not properly handled, may also enter the marine environment; major sources are poorly managed landfill sites, near the coast or on rivers, and also fly-tipping, although the original source of the debris may be many kilometres inland.
- Industrial products – through accidental loss during transport, *via* both land and sea, or as a result of inappropriate disposal methods, the marine environment can become contaminated with industrial materials. A familiar example of this is the presence of small pellets used to manufacture plastic items ('nurdles'), which are frequently identified during surveys of marine debris.
- Sewage related debris – this occurs when untreated sewage is discharged into the marine environment, either due to an absence of suitable waste treatment facilities, or as a result of storm events which lead to sewer overflows. Although SRD comprised only 5.4% of marine debris, as measured by the 2009 UK Beachwatch survey[125], its particularly unpleasant nature makes it rather troublesome[120].
- Storm water discharges – debris that has collected in storm drains may later be flushed into the marine environment during storm events.

6.3.2 Ocean-based sources of marine debris[120]

Discharges of marine debris may occur at sea from shipping, the fishing industry and offshore oil/gas installations, as a result of inadvertent activities, but also by deliberate means: the kinds of material entering the sea may range from simple galley waste, to entire shipping containers.

- The fishing industry – among the more visible items of marine litter are nets, ropes and other fishing debris, which have been abandoned, accidentally lost, or deliberately dumped by fishing crews, along with other kinds of waste.
- Shipping – it is estimated that across the world, annually, as many as 10,000 shipping containers are 'lost' in the oceans (usually due to storms). It is forbidden by international legislation to dispose of manufactured items at sea, but nonetheless, these continue to be accidentally lost overboard, stored insecurely, or deliberately discarded by shipping vessels, especially when they undertake long journeys.
- The leisure industry – owners and operators of boats used for recreational purposes, may also accidentally or deliberately discharge various forms of marine debris, for example, food containers, plastic bottles and fishing gear.
- Offshore oil and gas platform exploration – a wide range of different items may also be discarded from offshore oil and gas production facilities, which may include commonplace items such as gloves and hard hats, and also waste material produced by the exploration and resource extraction activities themselves.

7. Origin and fate of plastic pollution

Geographically, the five heaviest plastic polluters are P.R. China, Indonesia, Philippines, Vietnam and Sri Lanka, which between them contribute 56% of global plastic waste; this is mainly as a result of large populations living within 50 km of the coast, and relatively poor waste management facilities[62]. It has been estimated that more than 150 Mt of plastics has entered the world's oceans[21], which amounts to around 2.6% of the total plastic waste ever produced from primary plastics (5.8 billion tonnes)[2]. However, this is greater by more than two orders of magnitude than the quantities that have been reckoned to actually exist in the surface oceans. For example, Erikson *et al.* estimated that[51], at a minimum, some 5.25 trillion plastic particles are present there, with a combined mass of 268,940 tonnes, of which 202,800 tonnes is in the form of macroplastic (> 200 mm), 66,140 is of dimension < 200 mm, and of this 35,540 tonnes falls into the category of microparticles (< 5mm). Also using surface-trawling plankton nets, Cózar *et al.* determined[53] a range of 7,000–35,000 tonnes for the global mass of ocean plastic particles. On the basis of another study[126], it was determined that there are between 15 to 51 trillion (< 200 mm) particles present in the surface oceans, with a combined mass of between 93,000 and 236,000 tonnes. Despite these differences in standing stock estimates between the three studies, each one identifies the highest concentrations of net-collected plastics to be in the subtropical gyres (Section 7.1), and that the largest mass is contained in the North Pacific Ocean, most probably because its area is very large and that considerable amounts of plastic waste are discharged there from the USA and coastal Asian nations[62]. However, since at best only around 2% of even the plastic input of a single year is accounted for, and an order of magnitude less than even this, of the cumulative mass of plastic predicted to have been added to the oceans over the past several decades, the question arises of what has happened to all the missing plastic.

It has been speculated that some of it may be: in the form of macroplastic that has fallen to the seafloor or become beached; microparticles that have been absorbed into seafloor sediments; as dispersed and suspended through the ocean column down into the deep oceans; as consumed by fish and other marine organisms or by microbes; but the nature of the actual sink is presently far from clear[51,126]. However, the broad similarities between the results from the three studies[51,33,126] allow the conclusion to be drawn, with reasonable confidence, that the ultimate fate of buoyant microplastics is not at the ocean surface. As noted in Section 6.2, the primary mechanism for decomposing plastic is UV degradation, which initiates progressive fragmentation and embrittlement of the material. When the particles become smaller than the mesh size of the sampling net, they escape detection. Ingestion of small plastic particles by a broad range of species, either directly or indirectly, *via* their prey organisms[127–130] may provide a significant means for their removal from the ocean. Microplastics may also be caused to sink, either as a result of fouling by organisms, or by ingestion and incorporation into faecal pellets. The ability of some microbes to biodegrade microplastic particles[131–133] might be of further importance, particularly as the effective surface area increases through progressive fragmentation (Section 4.1.1) which improves the potential for biodegradation to occur. Accordingly, such incorporation of microplastics into ocean food webs might assist with the depletion of microplastics from the sea surface[75], but with as yet unknown effects on the organisms involved[70,134–136], and indeed the health of the overall marine ecosystem.

The situation is aptly summarised[126] by van Sebille *et al*.: ‘The order-of-magnitude discrepancies in these global-scale budgeting exercises reveal a fundamental gap in understanding akin to the ‘missing’ anthropogenic carbon dioxide in the carbon budgeting exercise of the early 2000s (*e.g.* Stephens *et al*., 2007 [see ref. 137]). Until these discrepancies are resolved at even a coarse scale, we cannot quantify the full suite of impacts of plastic debris on the marine ecosystem.’

7.1 Plastic pollution in the Pacific Ocean – the ‘great Pacific garbage patch’

Ocean gyres are vortices – swirling masses of water – in the open ocean. In the Pacific Gyre, specifically at the 20°N–40°N latitude, large bodies of water can be identified with floating marine debris[138].There are two main points of concentration: the western garbage patch (off the coast of Japan) and the eastern garbage patch (between Hawaii and California), and both are regions of the ‘great Pacific garbage patch’ (GPGP), being connected through a section of floating debris off the northern coast of the Hawaiian islands. The patch contains relatively high pelagic (*i.e.* in the water column of the open ocean) concentrations of plastics, chemical sludge, and other kinds of debris that are trapped and retained in the converging surface currents of the North Pacific Gyre[139] (Figure 15).

The term ‘garbage patch’ is misleading, and is often used by the media along with photographs of trapped plastic taken elsewhere, to imply there are vast islands of floating plastic waste in the open ocean; however, the plastic is mainly invisible, due

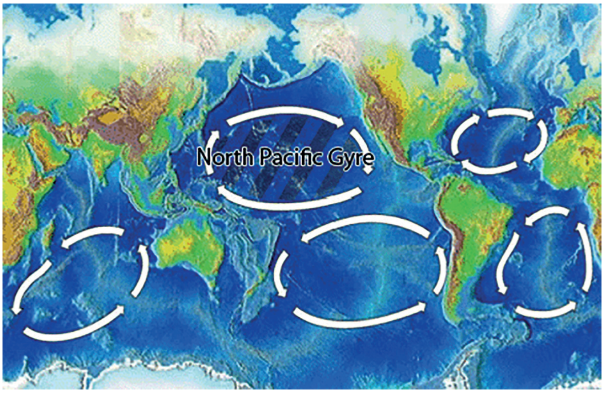

***Figure 15** The area of increased plastic particles is located within the North Pacific Gyre, one of the five major ocean gyres. Credit: Fangz, https://upload.wikimedia.org/wikipedia/commons/6/64/North_Pacific_Gyre_World_Map.png.*

to there being an average of around one particle per 1.5 m^2 of seawater, many of which are microscopic in size, and suspended in the upper water column below the surface of the ocean[139]. It has been estimated that there are at least 79,000 (45,000–129,000) tonnes of debris contained in the GPGP, occupying an area of 1.6 million km^2 (more than twice the size of France), within which the concentration of plastic ranges from 10–100 kg km^{-2} (see ref. 139). In terms of mass, more than three-quarters arose from debris larger than 5 cm and at least 46% was provided by fishing nets. Microplastics accounted for 8% of the total mass, but these comprised 94% of the estimated 1.8 (1.1–3.6) trillion plastic items floating in the area. Indeed, over 99.9% of the 1,136,145 pieces and 668 kg of floating debris collected by trawls was made of plastic. The plastic that was sampled exhibited particular features, for example a low surface-to-volume ratio, which suggests that the capacity to persist and accumulate at the surface of the GPGP is possessed by only certain kinds of plastic particles[139]. Of further significance is the indication that the level of plastic pollution in the GPGP is increasing exponentially and at a faster rate than is occurring in the surrounding water[139]. The North Atlantic garbage patch is the term used to describe a similar region of floating plastic debris in the Atlantic Ocean[140].

In April 2017, a report was published[141] which referred to 'the highest density of plastic rubbish anywhere in the world'. This was on the remote and uninhabited Henderson Island in the South Pacific (Figure 6), which acts as a dumping ground for marine debris – due to the flow of the South Pacific Gyre – where there is thought to be some 37.7 million items, with a combined mass of 17.6 tonnes. A total of 17–268 new items were washed up, daily, on a 10 m section of North Beach, and Purple Hermit Crabs (*Coenobita spinosus*) were observed to use plastic containers there as shelters to live in[142].

7.2 Pollution of the Great Lakes by microplastics

It has been found that the concentrations of microplastics in the Great Lakes rival those measured in the garbage patches of the world's ocean gyres. Thus, Eriksen *et al*. reported a maximum of > 466,000 particles per km^2 (see ref. 143) in the surface waters of the Great Lakes, with an average abundance of around 43,000 particles per km^2, and a median of 5,350 particles per km^2. Using the data of Eriksen *et al*., Baldwin *et al*. concluded[144] that, in the waters of the Great Lakes, on average 52% of the microplastics were present as fragments, and 16% as beads/pellets, while fibres/lines comprised just 2% of the total; the remainder was accounted for by foams and films (*ca* 18% and 11%, respectively). However, a strikingly different distribution of microplastic types was found for the tributary waters, with 71% of the particles being present as fibres/lines (the majority being fibres), with the rest being accounted for by fragments (17%), foams (8%), films (3%) and beads/pellets (2%). It is thought that these differences may, in part, reflect the nature of the different analytical methods employed, but also the various physical properties of the different types of plastics, *e.g.* some have a lower density than water, and thus are buoyant, while others are more dense and tend to sink in water[144]. Furthermore, the different water bodies will exhibit differential hydrodynamic behaviour, and so negatively buoyant fibres (*e.g.* those made from rayon, nylon, polyester and cellulose), may remain afloat in the turbulent currents of a river, but settle out in the calmer waters of a lake. In contrast, foams, films, beads/pellets, that are made from polystyrene, polyethylene and polypropylene, will tend to float in the surface waters of a lake, until they are caused to sink by befouling, or mineral absorption. Broadly the results are in accord with this scheme, and it is likely that fibres will tend to sink and accumulate in the lake sediments[144]. Indeed, near-shore sediments in Lake Ontario, showed a concentration of 980 microparticles per kg, which were mainly fibres and fragments. It is considered that such accumulations in lakebed sediments may affect benthic organisms, and consequently those at higher trophic levels which feed on them[145].

7.3 Global discharge of microplastics by rivers

Although the majority of the global population resides in coastal areas[146], due to the fact that river networks provide conduits between much of the Earth's land surface and the oceans, and because the majority of marine debris is thought to come from land-based sources, rivers provide a major route for the transport of plastic into the seas. It has been estimated[147,148] that somewhere in the range 0.47–2.75 Mt of plastic enters the oceans *via* rivers, and that 10 major rivers are responsible for 88–95% of the plastic that is thereby delivered to the oceans (Figure 16). Listing the top five, the greatest contributor is the Yangtze River, which delivers around 1.5 Mt (1.469 Mt) annually, followed by the Indus (0.164 Mt), the Yellow River (0.124 Mt), the Hai He (0.092 Mt), and the Nile (0.085 Mt); these may be compared with the mere 18 tonnes which is discharged into the oceans by the river Thames, annually, although this is still considered to be too much[149]. In each case, the bulk of the mass is in the form of macroplastic, and the ratio of microplastic/macroplastic is < 10% (see ref. 146). The above estimate for delivery of plastics to the oceans by rivers is in accord with a study[42] by Lebreton *et al*. (2017) from which it was estimated that 1.15–2.41 Mt per annum of plastic are delivered to the oceans by rivers.

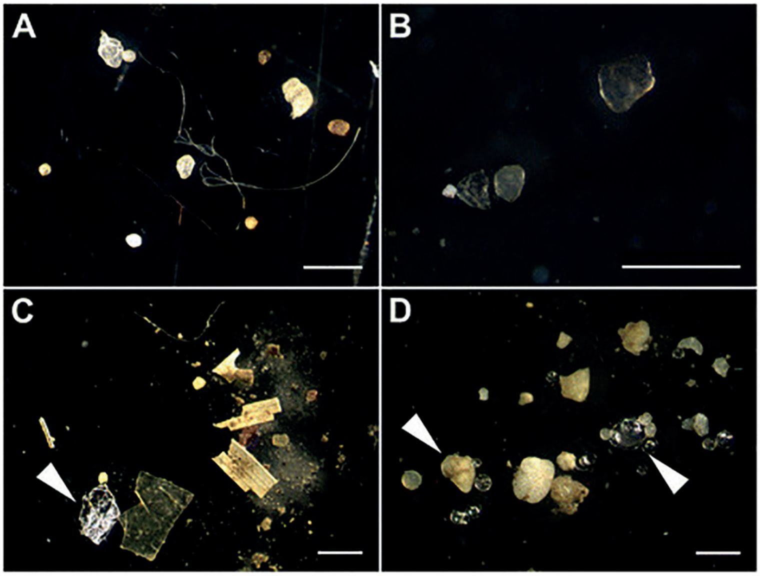

***Figure 16** Microplastics present in river sediments. Credit: Martin Wagner* et al.*, https://upload.wikimedia.org/wikipedia/commons/0/0a/Microplastics_in_sediments.jpg.*

7.4 Contamination of soils by microplastics

It is both surprising, and of potential concern, that microplastics have been detected in 90% of floodplain soils, sampled across Switzerland, a nation where nearly 100% of all plastics are recycled or incinerated, and hence there is a reduced likelihood for contamination from local sources of plastics than in many other parts of the world, where plastic waste is less well managed[150]. Indeed, the presence of microplastic particles (MPs) in remote, high mountain regions, without permanent residents and unaffected by sewage discharge, and in nature reserves, indicates they are widely and diffusely distributed, and most likely carried by the wind. As expected, a correlation was found between the concentration of MPs and the number of permanent inhabitants near a sampling site, since these arise from human activities[150]. Results from a study of shoreline sediment reported by Browne *et al.* showed a similar relationship[35]. Interestingly, when mesoplastic particles (MEP) (5 mm–2.5 cm diameter) were examined, there was no apparent correlation with the number of permanent residents; however, a correlation was identified between the concentrations of MPs and MEPs which suggests that the smaller particles were either formed from the larger MEPs or that common sources are responsible for both[150]. Although the measured concentrations of MPs were low in comparison with marine environments and polluted soils, the possibility that they may be harmful to soil organisms (and hence to the soil food web[25]) is suggested by recently acquired evidence that MPs are toxic to earthworms[151–153]. The authors[150] stress that it is therefore important to determine the toxicities of MPs to soil organisms, plants, and terrestrial animals, and also to assess the likelihood that such particles can enter the human food chain. In addition, they highlight the necessity to elucidate transport mechanisms in soils and exchange of MPs with the atmosphere and hydrosphere, in order that a full evaluation of the consequences of environmental plastic degradation can be made[150]. In view of the critical role of soils, and their organisms, in mediating many essential aspects of life on earth[25], the topic of soils and plastic pollution is likely to become one of increasing activity.

7.5 High concentrations of microplastics discovered in Arctic ice-cores

Very high concentrations of microplastics have been measured in cores taken from Arctic sea ice[154], the highest of which was $(1.2 \pm 1.4) \times 10^7$ particles m^{-3}, in a core taken from the pack ice of Fram Strait. The values are highly variable, but are two to three orders of magnitude larger than those determined previously in samples taken from the Central Arctic[155] $(1.3–9.6) \times 10^4$ particles m^{-3}, and is largely a consequence of the different methodologies that were employed in the two studies. Overall, 17 different kinds of polymer were identified, including polyethylene, varnish (including polyurethanes and polyacrylates), polyamide (nylon), ethylene vinyl acetate (EVA), cellulose acetate (CE), polyester and polypropylene, of which an average of 48% and 1.65% of the total measured MP composition, was contributed by PE and PP, respectively. The 'fingerprint' of the microplastics suggests they were carried on ocean currents from the Pacific garbage patch, but there is also some local origin due to pollution from shipping and fishing. The ability of the sea ice to trap and transport large quantities of microparticles across the Atlantic Ocean and to release them into the environment when the ice melts, particularly under the influence of a rising mean global temperature, is emphasised[154]. It is thought that, as resources are relentlessly exploited in the Arctic, its sea ice will tend to accrue increasing amounts of microparticles, which will be released in higher concentrations in locations where the seasonal sea ice melt and outflow gateways are the strongest.

8. Policy and legislation regarding plastic additives and microplastics

8.1 BPA

On 14 February 2018, the European Union published a Commission Regulation (EU) 2018/213 'on the use of bisphenol A in varnishes and coatings intended to come into contact with food and amending Regulation (EU) No 10/2011 as regards the use of that substance in plastic food contact materials'. This established a specific migration limit for the leaching of BPA from varnishes and coatings (packaging) of 0.05 mg kg^{-1} into food. This revision reduces the limit for BPA from 0.6 mg kg^{-1}, as in the previous Regulation 10/2011, to 0.05 mg kg^{-1} of food. Furthermore, it extends the ban on BPA in polycarbonate plastics intended for use in infant feeding bottles, and any other items designed to come into contact with foodstuffs for young children[156]. The US Food and Drug Administration (FDA) had previously banned[157] the use of BPA in baby's bottles and 'sippy cups' on 17 July 2012.

Responding to the more recent pre-peer review draft report[158] on the safety of BPA, the FDA issued the following statement[159]: 'One area that has been of significant consumer interest is the use of Bisphenol A (BPA) in food packaging. BPA is authorized for use in polycarbonate plastics and epoxy resins in certain food and beverage can linings. Given this interest, the FDA has routinely considered and evaluated the scientific evidence surrounding the use of BPA and continues to conclude that BPA is safe for the currently authorized uses in food containers and packaging.'

However, some scientists have described[160] the FDA statement as 'premature'. In an effort to provide safer 'BPA substitutes', alternative compounds such as bisphenol S (BPS), bisphenol F (BPF), bisphenol AP (BPAP), bisphenol AF (BPAF), bisphenol Z (BPZ) and bisphenol B (BPB), have been introduced. However, when these materials were examined for their oestrogen receptor activity, some of them showed a greater potency than BPA in activating the oestrogen receptor, which strongly signals the need to screen any 'substitutes' in order to prove that they are safer than the chemical being replaced, before introducing them to the commercial arena[161].

8.2 Phthalates

8.2.1 Europe

Although controversial, the restriction of phthalates in plastics for children's toys has been in place in the European Union since 1999[162], and which sets an upper limit of 0.1 mass% of phthalate in the plasticised part of the toy. Di(2-ethylhexyl) phthalate (DEHP), butylbenzyl phthalate (BBP), and dibutyl phthalate (DBP), are restricted universally, while the restriction for diisononyl phthalate (DINP), diisodecyl phthalate (DIDP), and di-*n*-octyl phthalate (DNOP) only applies to toys that a child can put into its mouth. It is the phthalates, DINP, DIDP and di(2-propylheptyl) phthalate (DPHP), which are of high molecular weight that have been registered under REACH and their safety for current applications has been demonstrated. In 2008–2009, the lower molecular weight phthalates, BBP, DEHP, diisobutyl phthalate (DIBP), and DBP were included on the Candidate List of Substances for Authorisation under REACH, and in 2011, were added to the Authorisation list, Annex XIV[163]. On 20 June 2017, the Socio-Economic Analysis Committee of the European Chemicals Agency voted to further restrict the use of BBP, DEHP, DBP, and DIBP, under REACH; the latter protocol was first used to control them in 2015, but the proviso was left for authorisations to be applied for, to still use them, if safer substitutes were unavailable. However, the proposed further controls would mean that no such continued-use license could be sought for any consumer products containing > 0.1 mass% of phthalate[164,165].

8.2.2 U.S.A.

In the USA, similar restrictions became law in February 2009, in which it is stated that 'it shall be unlawful for any person to manufacture for sale, offer for sale, distribute in commerce, or import into the USA any children's toy or child care article that contains concentrations of more than 0.1% of DEHP, DBP, or BBP and it shall be unlawful for any person to manufacture for sale, offer for sale, distribute in commerce, or import into the USA any children's toy that can be placed in a child's mouth or child care article that contains concentrations of more than 0.1% of DINP, DIDP, DNOP.' Prior to this legislation, the Consumer Product Safety Commission had concluded that a ban on phthalates was unnecessary, because voluntary withdrawals of DEHP and DINP from teethers, pacifiers, and rattles had eliminated the risk to children[166]. On 27 October 2017, the US Consumer Product Safety Commission (CPSC) published a Final Rule, to amend its Regulation to limit phthalate concentrations in toys and other products to be used by children, which will become effective for products manufactured or imported on or after 25 April 2018 (180 days following publication in the Federal Register). In summary, the Final Rule addresses the following matters[167]:

- Removal of the 1000 ppm (0.1 mass%) limit for di-*n*-octyl phthalate and diisodecyl phthalate.
- The interim ban on diisononyl phthalate has been made final and expanded to include all toys.
- A limit (0.1 mass%) has been established for diisobutyl phthalate, di-*n*-pentyl phthalate (DPENP), di-*n*-hexyl phthalate (DHEXP) and dicyclohexyl phthalate (DCHP).
- The scope has been expanded to include all accessible components of all toys and childcare articles, for the eight phthalates considered; the present limit had previously only applied to toys that may be taken into the mouth, and for certain phthalates.

8.3 Microplastics

Various groups and campaigns are advocating the banning of microplastics, one of the more vocal being the 'Beat the Microbead' movement, which aims to ban plastic microbeads from personal care products[168]. As prominent an organisation as UNESCO has provided support for research programmes that address microplastic pollution in the global context, since the dimension and nature of the problem crosses formal regional boundaries[169]. The European Commission has asked the European Chemicals Agency (ECHA) to prepare a REACH Annex XV restriction dossier on the use of intentionally added microplastic particles to all consumer and professional use products[170]. This is within the framework of the European Plastics Strategy[171] published on 16 January 2018, which sets out means to reduce plastic waste, and is set within the concept of the circular economy[172]. The overall intention is that by 2030, all plastic packaging is recyclable, with a significant reduction in the use of plastics for once-through applications. It is thought that around 300,000 tonnes of plastic waste enters the marine environment in Europe, and the European Plastics Strategy explicitly describes measures to reduce the use of microplastics, and involves better monitoring and mapping of marine litter, including microplastics. As other sources of microplastics, dust from tyres, microfibres from textiles, and microparticles from paints will also be considered. The plastics strategy is included along with four others, namely: food waste; critical raw materials; construction and demolition; biomass and bio-based products, as part of the 'EU Action Plan for the Circular Economy'[173]. ECHA anticipates that it will submit the microplastics restriction dossier on 11 January 2019. On 9 January 2018, a ban came into force on the use of microbeads in personal care products and cosmetics, manufactured in the UK[174]; this will be followed on 30 June by a ban on the sales of all such products[174]. In the USA, Illinois was the first state to impose a degree of restriction on cosmetics containing microbeads, followed by various other states[175], while at the Federal level, the Microbead-Free Waters Act 2015[176] was enacted after being signed by President Barack Obama on 28 December 2015. As the Act states, it is effective:

'(A) with respect to manufacturing, beginning on July 1, 2017, and with respect to introduction or delivery for introduction into interstate commerce, beginning on July 1, 2018; and;

(B) notwithstanding subparagraph (A), in the case of a rinse-off cosmetic that is a nonprescription drug, with respect to manufacturing, beginning on July 1, 2018, and with respect to the introduction or delivery for introduction into interstate commerce, beginning on July 1, 2019.'

9. Efforts to reduce plastic waste

9.1 Non-usage and reduction in usage of plastics

There have been various efforts made to reduce the amount of plastics used, and to promote recycling of plastic goods. The toy company, LEGO has announced its plans to begin making its famous plastic bricks from sustainable polyethylene, rather than from petroleum based sources[177]. Many UK supermarkets have introduced charges to their customers for plastic bags, and biodegradable materials are also now being used, or bags are commonly on sale that are made of more durable and natural materials, such as cotton, hessian, or linen. Plastic disposable water bottles, and plastic carrier bags, are banned by some businesses and communities, and some regional authorities have pledged to introduce public drinking fountains, so that water bottles can be refilled[178]. Every year, in the UK, almost 2.5 billion disposable cups are used, which due to their composite nature[179] (plastic lining on a paper cup), are very difficult to recycle, and hence mostly go to landfill. In Reading, the largest town in the UK, the 'Refill Reading' campaign[180] has been introduced – as a project of 'Transition Town Reading' – which encourages people to instead purchase a refillable cup (made from sustainably sourced bamboo) which is accepted by local coffee shops, many of whom offer a reduction of around 10% from the normal price of a cup of coffee, as served in a disposable cup. Local initiatives such as Repair Cafes and Remakery[181] assist in repairing/reutilising items that would otherwise be disposed of, and hence decrease the amount of plastic and other kinds of waste, along with reducing the use of energy that is mostly derived from fossil fuels[182].

The 2015 National Games of India, held in Thiruvananthapuram, was made 'disposable-free', by imposing a ban on the use of plastic water bottles[183], which led to an increased use of tumblers, made from stainless steel, and other reusable tableware items, rather than the usual throw-away plastic cutlery[183]. Refillable steel flasks were provided to athletes, and overall it is reckoned that 120 tonnes of disposable waste was avoided during the event[183]. The Indian Ministry of Drinking Water and Sanitation, has encouraged governmental departments to make alternative arrangements for providing drinking water that do not generate waste from plastic bottles[183]. Similarly, the states of Sikkim and Bihar have restricted the use of plastic water bottles and Styrofoam drinking cups at government meetings[183].

The world's most draconian ban on plastic bags was imposed in Kenya on 28 August 2017, where anyone producing, selling – or even just carrying – a plastic bag can receive a jail sentence of to up to four years, or a fine of USD 40,000 (see ref. 184).

9.2 Plastic recycling

The rates of plastic recycling in Europe, China, and the USA, are 30%, 25% and 9%, respectively[2]; however, it is estimated that roughly half of the global production of solid plastic is thrown away each year, *i.e.* in excess of 150 Mt, and that 20% of global plastic waste is generated in the USA[185]. Of the \$11.4 billion dollars that packaging waste in US landfill sites is reckoned to be worth, \$8.3 billion is ascribed to plastic waste[186]. There are also energy savings to be had, since up to *ca* 130 GJ of energy per tonne can be saved through recycling plastic, rather than producing primary new material. The statistic has been given that, if all global plastic waste were recycled, the equivalent of 3.5 billion barrels of oil would be saved, which is worth approximately \$176 billion dollars (at \$50 per barrel)[187]; however, the latter figure is merely illustrative, since it accounts for the total energy in terms of the energy content of oil, which, in fact, is rarely used as a fuel for plastic manufacture. Rather, the major saving would be in terms of the oil/NGLs used as chemical feedstocks from which virgin plastic is made. The principal saved energy inputs would be from gas and coal (and uranium) to make electricity, and from gas itself, burned to provide heat at various points in the plastic manufacturing cycle, with a smaller amount of oil being refined to provide fuel for the transportation/distribution network.

Overall, however, some 3.5% of total global energy use[188,189] could be saved by recycling all the plastic waste generated across the world, in addition to around 150 Mt of oil/NGLs as hydrocarbon feedstocks (assumed equal to the amount of annually produced plastic that ends up as waste[2]). Although the precise numbers can be debated, which depend in part on the prevailing oil price, there is clearly considerable scope for reducing the use of virgin fossil resources, and in providing business opportunities: thus, it has been estimated that 53% (see ref. 21) of plastic packaging in Europe could be recycled 'eco-efficiently'. Currently, the only widely employed method for recycling plastic is mechanical, in which the organic component is recovered by washing, and is then shredded, melted and remoulded – frequently in a mixture with virgin plastic of the same type – so that it can be used to manufacture new plastic goods. Since this approach cannot be applied to thermosets and composites, only PET and different types of PE, are recovered by mechanical processing, which respectively account for 9% and 37% of all plastics manufactured, while no more than 1% of the remainder is recovered[190]. Chemical recycling includes methods such as catalytic pyrolysis, which uses the plastic as a feedstock for the production of gases, waxes, or fuels; however, it is not widely employed, due to the high energy consumption involved[191]. A potentially promising advanced method for plastic recycling is depolymerisation, although necessary catalysts must be developed that can perform the process efficiently, without decomposing particular functional groups, and at both adequate energy and financial costs. It is noteworthy that the depolymerisation of PE has been accomplished at a low temperature of *ca* 150 °C, using a cocatalyst, although this did not yield the ethylene monomer[192]. Efforts are also being made to find ways to process directly waste that contains mixtures of plastics, in order to avoid the laborious sorting of individual types of plastic from municipal waste. This is extremely challenging, due to the immiscibility of different kinds of plastic, and that only a small quantity of one type present in another can profoundly alter its properties, often making it unsuitable for a particular purpose; however, this problem can be obviated through the use of compatibilisers – which are generally multicomponent polymers of various architectures – designed to confer particular physical properties to the polymer mix so that it can be tailored for given purposes. The analogy has been given of a surfactant, which enables different components such as oil and water to mix[185]. Since plastics such as PET can be depolymerised back to their original starting monomers – in the case of PET itself, terephthalic acid plus ethylene – virgin PET polymer can be created by repolymerising them. A high molecular mass polymer has been developed with properties comparable to those of commercially used plastics, but which is intrinsically, infinitely recyclable. It is based on a five-membered ring cyclic monomer derived from γ-butyrolactone, and can be made under mild conditions, and at ambient temperature. The polymer was found to be highly crystalline and thermally very robust, and yet, when the temperature was raised sufficiently high (or at cooler temperatures in the presence of a zinc chloride catalyst), it could be returned to its starting monomers, and reconverted into new material, so constituting a perpetual recycling process[193].

The UK government's chief environmental scientist has suggested plastic waste should be stored in landfill for the time being, and later 'mined' when better technology has been invented to convert it into useful products[194]. It has also been proposed that plastic waste could be used to construct roads and pavements, although the issue is complex[195]. In one formulation, actually in use, just 0.3–1.0% (3–10 kg tonne^{-1}) is plastic waste, and the rest is asphalt (3–10 kg tonne^{-1})[196]. Another study proposes that 5% plastic waste would be optimum for pavement construction[197]. However, as we have seen in Section 4.1.1, there is potentially the risk that abrasion of these composites could result in the production of microplastics.

9.3 Plastics and the circular economy

The Ellen MacArthur Foundation was established in 2010 with the aim of accelerating the transition to a circular economy[198]. Plastic waste, particularly from packaging, features prominently in this scheme, as is described in the report[21], 'The New Plastics Economy – Rethinking the Future of Plastics'. In summary, the consequences of the plan being actuated would be: more effective collection/recycling, meaning a reduction in the amount of plastic going to landfill, and hence less plastic entering the environment; a decoupling of plastics manufacture from fossil resources, and more production from sustainable sources; a less rapid use of finite fossil resources (oil/gas/NGLs); a smaller, and more efficient use of energy, thus leading to a reduction in CO_2 emissions[21]. On 26 April 2018, together with the Foundation, the Waste and Resources Action Programme (WRAP) launched the 'UK Plastics Pact'[199], which is an industry-wide initiative with the goal to transform the use of packaging and reduce plastic waste, and has so far been signed up to by 42 businesses, including the majority of the UK's major supermarkets. Among the Pact's aims are that, by the year 2025, all plastic packaging in use can be reused, recycled or composted.

9.3.1 EU circular economy – plastics

The European Commission plan for a circular economy[173], includes a specific component for the use of plastics more effectively and with the production of less waste[200]. The section of the document entitled 'A vision for Europe's new plastics economy' offers the following[200]:

'A smart, innovative and sustainable plastics industry, where design and production fully respects the needs of reuse, repair, and recycling, brings growth and jobs to Europe and helps cut EU's greenhouse gas emissions and dependence on imported fossil fuels.'

Among the proposed specific measures are:

- 'Plastics and products containing plastics are designed to allow for greater durability, reuse and high-quality recycling. By 2030, all plastics packaging placed on the EU market is either reusable or can be recycled in a cost-effective manner.
- Changes in production and design enable higher plastics recycling rates for all key applications. By 2030, more than half of plastics waste generated in Europe is recycled. Separate collection of plastics waste reaches very high levels. Recycling of plastics packaging waste achieves levels comparable with those of other packaging materials.
- More plastic recycling helps reduce Europe's dependence on imported fossil fuel and cut CO_2 emissions, in line with commitments under the Paris Agreement.
- Innovative materials and alternative feedstocks for plastic production are developed and used where evidence clearly shows that they are more sustainable compared to the non-renewable alternatives. This supports efforts on decarbonisation and creating additional opportunities for growth.
- Europe confirms its leadership in sorting and recycling equipment and technologies. Exports rise in lockstep with global demand for more sustainable ways of processing end-of-life plastics.

‘In Europe, citizens, government and industry support more sustainable and safer consumption and production patterns for plastics. This provides a fertile ground for social innovation and entrepreneurship, creating a wealth of opportunities for all Europeans.

- ‘Plastic waste generation is decoupled from growth. Citizens are aware of the need to avoid waste, and make choices accordingly. Consumers, as key players, are incentivised, made aware of key benefits and thus enabled to contribute actively to the transition. Better design, new business models and innovative products emerge that offer more sustainable consumption patterns.
- The leakage of plastics into the environment decreases drastically. Effective waste collection systems, combined with a drop in waste generation and with increased consumer awareness, avoid litter and ensure that waste is handled appropriately. Marine litter from sea-based sources such as ships, fishing and aquaculture are significantly reduced. Cleaner beaches and seas foster activities such as tourism and fisheries, and preserve fragile ecosystems. All major European cities are much cleaner.
- Innovative solutions are developed to prevent microplastics from reaching the seas. Their origin, routes of travel, and effects on human health are better understood, and industry and public authorities are working together to prevent them from ending up in our oceans and our air, drinking water or on our plates.
- The EU is taking a leading role in a global dynamic, with countries engaging and cooperating to halt the flow of plastics into the oceans and taking remedial action against plastic waste already accumulated. Best practices are disseminated widely, scientific knowledge improves, citizens mobilise, and innovators and scientists develop solutions that can be applied worldwide.’

9.4 Deliberate degradation of plastic waste

While not addressing the consumption of finite fossil hydrocarbons to make plastics in the first place, schemes have been mooted to reduce the volume of the resulting plastic waste, and to mitigate the consequent environmental contamination[201]. For example, a bacterium, *Ideonella sakaiensis* 201-F6, was recently identified, which displayed the remarkable ability to use PET as a major carbon and energy source for its growth[202]. It was discovered that, as an essential component of its metabolic strategy, the bacterium secretes an enzyme that can degrade PET, and which has accordingly been given the name ‘PETase’. Unexpectedly, although the bacterium had evolved in a plastic-rich environment (landfill), it was recognised that the PETase enzyme could be improved further towards PET degradation, by means of protein modification[203], which indicates that, in its natural form, it is not fully optimised to consume crystalline PET. PETase was found to depolymerise PET primarily to mono(2-hydroxyethyl) terephthalic acid (MHET) units, along with minor quantities of terephthalic acid (TPA) and bis(2-hydroxyethyl)-TPA. An additional enzyme, MHETase, which is also secreted by *I. sakaiensis*, then comes into play, which uses MHET as a substrate, and converts it into the initial

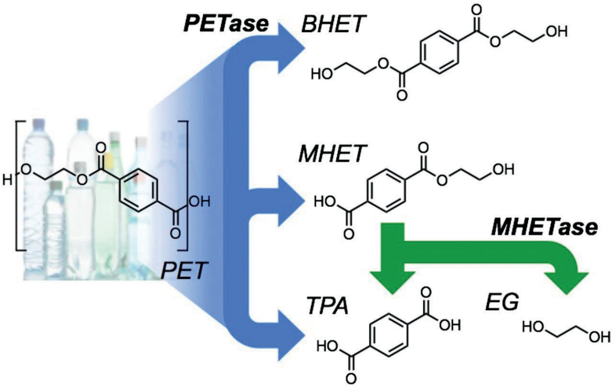

Figure 17 *PETase catalyses the depolymerization of PET to bis(2-hydroxyethyl) - TPA (BHET), MHET, and TPA. MHETase converts MHET to TPA and EG. Reproduced with permission from* Proceedings of the National Academy of Sciences (PNAS) *(see ref. 201).*

two monomers, TPA and ethylene glycol (EG), from which the PET polymer was originally synthesised (Figure 17). Thus, there is a synergistic interplay between the two enzymes, in the overall biodegradation of PET. The fact that PETase is not capable of acting on aliphatic polyesters would indicate that it is an aromatic polyesterase, an inference that is supported further by its ability to degrade another semiaromatic polyester, polyethylene-2,5-furandicarboxylate (PEF). The latter result is potentially important, in view of the bio-derived nature of PEF, which is being inaugurated as a potential substitute for PET, and hence for the fossil hydrocarbons from which the latter is derived. It is thought that protein engineering might serve to further improve this enzyme, and indeed to develop others with the capacity to cope with different types of plastic, and that more research into ‘structure-activity’ relationships is necessary to advance the field and its potential applications for ameliorating plastic waste[203]. In a sense, strategies of this kind might be compared with incineration, as another means to destroy plastic and keep it out of the environment; and indeed the question arises of what the overall energy costs might prove to be, if the approach is to be used on a scale commensurate with the vast mass/volume of plastic that is produced and consumed globally. However, while incineration contributes to the burden of greenhouse gases (albeit that heat can be recovered from the process), the decomposition products from the enzyme degradation process might be reused (recycled) back into new polymers (*e.g.* PET), or used for other manufacturing purposes, thus saving on the consumption of ‘new’ fossil resources.

9.4.1 Oxo-biodegradable plastics

The use of oxo-biodegradable plastics (sometimes referred to as oxo-degradable plastics, or oxo-plastics) has proved controversial. Celebrated as a less persistent alternative to conventional plastics, which may take many years to degrade under environmental conditions (Section 6.2), the criticism has been levelled that these materials do not fully biodegrade, but rather disintegrate into microplastic fragments, and are therefore harmful to the environment similarly to petroleum-based plastics[204]. Oxo-biodegradable plastics are made from traditional plastics such as PE, PP, PS, and PET, by incorporating oxidation catalysts into them, usually transition metals such as cobalt, manganese, and iron, which cause the plastic to fragment as a result of oxidation of the polymer chains. The initial energy trigger may be UV radiation or heat. The resulting fragments are intended to undergo subsequent biodegradation (Section 6.2). Indeed, the term 'oxo-degradable' refers to the initial oxidative fragmentation of the polymer, and it is the degree and rate of subsequent biodegradation that is at issue. Legislation has been passed in 15 countries[205], to encourage the replacement of conventional plastics by oxo-biodegradable plastics, especially for carrier bags, although it is a matter of debate whether this will obviate the problem of plastic litter contaminating the open environment.

The Ellen MacArthur Foundation issued its 'Oxo-statement' report[204], on 5 November 2017, which was supported by 150 organisations, calling for a ban on oxo-biodegradable plastic packaging (including carrier bags), on the grounds that the latter, 'is not a solution to plastics pollution, and does not fit in a circular economy'. However, the Oxo-Biodegradable Plastics Association (OPA) argued the report to be inaccurate, and claimed that many of the organisations who had signed their support had vested interests in a rival technology called 'bio-plastic'[206]. They further contended that when oxo-degradable plastics degrade, the process is not merely one of fragmentation, but a 'change of the material from a high molecular weight polymer, to monomeric and oligomeric fragments, and from hydrocarbon molecules to oxygen-containing molecules which can be bioassimilated'[206].

On 16 January 2018, the European Commission published its report on the use of oxo-degradable plastic[207]. This forms part of the 'European Strategy for Plastics in a Circular Economy' document[208] which was released on the same day. The EU concluded that:

'There is no evidence that oxo-degradable plastic will subsequently fully biodegrade in a reasonable time in the open environment, in landfills or in the marine environment. Sufficiently quick biodegradation is in particular not demonstrated for landfills and the marine environment.

'There is a considerable risk that fragmented plastics will not fully biodegrade and a subsequent risk of an accelerated and accumulating amount of microplastics in the environment, especially the marine environment. The issue of microplastics is long acknowledged as a global problem in need of urgent action, not just in terms of clean-up of littering but also of plastic pollution prevention.

'Claims presenting oxo-degradable plastic as an "oxo-biodegradable" solution to littering which has no negative impact on the environment, in particular by not leaving any fragments of plastic or toxic residues behind, are not substantiated by evidence.

'In the absence of conclusive evidence of a beneficial effect on the environment and indeed indications to the contrary, given the related misleading claims to consumers and risks of resulting littering behaviour, EU wide measures should be considered. Therefore, in the context of the European plastics strategy, a process to restrict the use of oxo-plastics in the EU will be started.'

A rebuttal to the EC report was issued by the OPA, claiming that the latter contained fundamental misunderstandings about the nature of oxo-biodegradable plastics, and that its use of external reports was inappropriate, including that by the Ellen MacArthur Foundation, whose findings it had previously contested[209].

9.5 Bioplastics

Some plastics that are termed ‘biodegradable’, are composite materials fabricated from starch, along with petrochemically derived plastics, and do not degrade fully, but disintegrate into plastic fragments, and may provide a source of microplastics in the environment[57]. Other bioplastics are derived fully from renewable sources of biomass, which include vegetable fats and oils, corn starch, cellulose and lactic acid[201], or they can be made from agricultural waste and from disposed-of plastic bottles and other containers by microbial degradation. Broadly, bioplastics are designated according to their generational order[21]:

‘First generation: biomass from plants that are rich in carbohydrates and that can be used as food or animal feed (*e.g.* sugar cane, corn, and wheat).

2nd generation: Biomass from plants that are not suitable for food or animal feed production. They can be either non-food crops (*e.g.* cellulose) or waste materials from 1st-generation feedstock (*e.g.* waste vegetable oil, bagasse, or corn stover).

3rd generation: Biomass derived from algae, which has a higher growth yield than either 1st- and 2nd-generation feedstock, and therefore has been allocated its own category.’

In addition to being sourced from renewable materials, bioplastics such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and cellulose are ‘biodegradable’, whereas versions of plastics of biological origin, such as PE (made from biologically produced ethane), naturally behave in the same way as their petrochemically derived counterparts. Despite the fact that, at first sight, bioplastics appear to offer many advantages[201] over their more established petroleum based counterparts, any future expansion of their use will begin from a very low baseline production level: thus, the global production of plastics derived from biological sources in 2017 was 2.05 Mt (see ref. 210), which is equivalent to just 0.5% of the total of 407 Mt that were produced in 2015, the remainder being derived from fossil hydrocarbons[2].

Plastics that can be decomposed in the environment by microorganisms are termed biodegradable, and those that are more resilient are referred to as durable. For a plastic to be truly ‘compostable’, it must be degradable by microorganisms to nutrient-rich organic material that can be added to nourish and enrich soil (*i.e.* as normal compost[25]), rather than being converted to greenhouse gases (*e.g.* CH_4 and CO_2).

Many biodegradable bioplastics require industrial composting facilities to fully break them down[201], which run at high temperatures, and may not decompose so effectively in a garden compost heap/bin. Moreover, during the latter, slower process, methane may be emitted, which is a potent greenhouse gas[123]. They may also not degrade well in the open environment, *e.g.* in the oceans, where oxygen levels are relatively low. Degradable materials can be made, that are not bioplastics but petrochemically derived, and are similar to other conventional plastics, but which contain additives to aid their degradation (*e.g.* oxo-plastics; Section 9.4.1). However, in a study of PE and PET, containing five different additives, supposed to promote biodegradation of the polymers, none of them made any significant difference, even after three years buried in three different environments: with oxygen (as in compost); buried without oxygen (as in a landfill); and simply buried in soil[211]. The use of carrier bags made from cassava hit the headlines recently[212], as a way to avoid plastic pollution, since the material degrades fairly rapidly in the environment, and even in hot water, and also 'edible 6-pack rings' made from barley and salt, that are fully biodegradable and which can serve as 'food' for animals, rather than injuring or killing them[213], have been introduced. Other industries create 'sustainable' products, based on crop-waste rather than petrochemicals, but the question arises of whether any such scheme can be truly sustainable, if it relies on the application of artificial fertilisers to maintain the fertility of soil that could more naturally have been provided by returning plant rubble to the land[25]? The same issue has been raised, as it was for biofuels, of the need to use non-food feedstocks to make bioplastics, to avoid competition between the use of land to grow crops for food or technology[214]. Indeed, whether this problem applies to bioplastics depends on the scale of production intended. To make 1 tonne of bio-PET requires an input of 5.7 tonnes of sugar cane, and it is expected that a land area of around 1.4 million hectares will be required by 2019 to meet the expected expansion of the bioplastics industry. It is thought that the anticipated tripling of global production will occur in Asia, where land degradation, habitat loss, reduced water quality, and land conflicts are already attendant factors to large scale biomass production[214]. This raises further issues as to how 'sustainable' it is to replace oil-derived plastics with bioplastics, especially given that oil and gas remain essential inputs[25] to the kind of agriculture used for this production.

10. Actions taken to raise awareness about plastic pollution

On 11 April 2013, in order to raise awareness about plastic pollution, The Garbage Patch State – an ongoing transmedia environmental artwork – was founded by artist Maria Cristina Finucci, under the patronage of UNESCO and the Italian Ministry of the Environment[215]. A plastic whale sculpture, called 'Plasticus', has been created[216] to emphasise the problem of plastic pollution of the oceans: the 'whale' is made from a quarter of a tonne of waste plastic, which is the amount reckoned to enter the oceans every second[216]. The BBC recently screened its *Blue Planet II* series, narrated by Sir David Attenborough, which in the final episode, addressed plastic pollution of the oceans directly[217]. Plastic was also mentioned in the text of the *Laudato Si*, encyclical letter[218] from Pope Francis, 'On Care for Our Common Home', in the context of excessive consumerism and the moral imperative to curb our use of fossil resources[219].

11. Conclusions

Since 2004, the world has made as much plastic as it did in the previous half century, and it has been reckoned that the total mass of virgin plastics ever made amounts to 8.3 billion tonnes, mainly derived from natural gas and crude oil, used as chemical feedstocks and fuel sources. In 2015, 407 Mt of plastics was produced, of which 164 Mt was consumed by packaging (36% of the total). It appears that, of all the plastics produced to date, 2.5 billion tonnes (30%) are currently in use, and between 1950 and 2015, the cumulative generation of primary and secondary (recycled) plastic waste amounted to 6.3 billion tonnes, of which 9% had been recycled (just 10% of this having been recycled more than once), 12% incinerated, and the remaining 79% either ended up in landfills or in the natural environment. Although quoted values vary, packaging probably accounts for around one third of all plastic used, of which approximately 40% goes to landfill, while 32% escapes the collection system: that is, either it is not collected at all, or is collected but then illegally dumped or mismanaged, and ends up directly in the environment. Only 28% of packaging waste had been collected, of which half was incinerated to provide energy, while the other half was recycled. The prognosis is that, should current trends maintain, by 2050 there will be of the order of 12 billion tonnes of plastic waste either in landfills or in the natural environment, and more plastic than fish in the seas (by mass). It was deduced that around 9 Mt of plastic entered the oceans in 2010, as a result of mismanaged waste, along with up to 0.5 Mt each of microplastics from washing synthetic textiles, and from the abrasion of tyres on road surfaces. It is estimated that in the region of 2 Mt of plastic pollution is delivered to the oceans by rivers, each year.

However, the amount of plastic actually detected in the oceans represents only a small fraction of this, and less than 1% of the total mass of plastics reckoned to have been released into the oceans over time (at least 150 Mt). It has been speculated that some of this ‘missing plastic’ may be: in the form of macroplastic that has either fallen to the seafloor or become beached; microparticles that have been absorbed into seafloor sediments, or dispersed and suspended through the ocean column down into the deep oceans, or consumed by fish and other marine organisms or by microbes; however, the nature of the actual sink is presently far from clear. It may nonetheless be concluded, with reasonable confidence, that the ultimate resting place for buoyant microplastics is not at the ocean surface. Plastic accounts for around 10% by mass of municipal waste, but up to 85% of marine debris items – of which land-based sources account for up to 80%, with at least 20% of the remainder being attributed to intentional or accidental abandonment, disposal or loss of goods, equipment and waste at sea.

Geographically, the five heaviest plastic polluters are P.R. China, Indonesia, Philippines, Vietnam and Sri Lanka, which between them contribute 56% of global plastic waste. Larger, primary plastic items can undergo progressive fragmentation to yield a greater number of increasingly smaller ‘secondary’ microplastic particles, thus increasing the overall surface area of the plastic material, which enhances its biological activity, and ability to absorb, and concentrate, persistent organic pollutants such as DDT and PCBs, with the potential to transfer them to the tissues of animals that ingest the microplastic particles, particularly in marine environments. While fears that such microparticles and their toxins may be passed *via* food webs to humans, are not as yet substantiated, the direct ingestion of microplastics by humans *via* drinking water is a distinct possibility – since 92% of samples taken in the USA and 72% in Europe showed their presence – although any consequent health effects are as yet unclear. Foodstuffs may also become contaminated by microplastics from the air, although any resultant health effects are also unknown. In regard to such airborne sources, it is noteworthy that small plastic particles have been found in human lung tissue, having been inhaled, which might prove an adverse health factor under given circumstances. It is also very striking that microplastics have been detected in mountain soils in Switzerland, which are most likely windborne in origin. Arctic ice core samples too, have revealed the presence of microplastics, the 'fingerprint' of which suggests they were carried on ocean currents from the Pacific garbage patch, or arose locally due to pollution from shipping and fishing. Thus, sea ice traps large amounts of microplastics and transports them across the Arctic Ocean, but such particles will be released into the global environment when the ice melts, particularly under the influence of a rising mean global temperature.

Although there is a growing emphasis toward the substitution of petrochemically derived plastics by bioplastics, controversy has arisen in regard to how biodegradable the latter actually are in the open environment, and any meaningful increase in their market share would need to grow substantially from the current very low level of just 0.5% of the total mass of plastics that are manufactured globally. The use of oxo-plastics, which contain additives that assist the materials to degrade, is also a matter of concern, since it is claimed that they merely break down into smaller pieces and add to the environmental burden of microplastics; the European Union has accordingly moved to restrict their use. Furthermore, since the majority of bioplastics are made from sugar and starch materials, the prospect arises of competition between growing crops to supply food or plastics, similarly to the issue that pertains over the diversion of food crops to the manufacture of primary biofuels. Many plastics that are described as biodegradable do not decompose well in the open environment, *e.g.* in the oceans, but require industrial composting facilities to break them down.

It has been argued that the use of plastic packaging ameliorates food waste, since food 'goes off' less quickly, and can thus be transported over greater distances and longer timescales, when it is protected by plastic. However, a counterview is that consumers are thereby encouraged to buy an excess of food, which they later throw away. Indeed, the use of plastic packaging has become a central part of our industrialised food production and distribution system, which is underpinned by inputs of fossil resources (oil, gas and coal) to provide energy, fertilisers, pesticides, herbicides, and indeed the plastics themselves. Plastic pollution is just one problem of industrialised culture, which cannot be addressed entirely by the same kind of industrialised thinking that created it.

There are very many uncertainties regarding the likely outcomes of plastic waste accumulating in the environment, but it is generally acknowledged that such material does not belong in the oceans, and indeed, having entered them, may pose a planetary boundary threat[220]. Thus, the precautionary principle should apply, as in addressing other global issues such as pollinator decline[221]: that is, while all the facts are far from known, the prevailing evidence indicates that a major problem may very likely exist, whose consequences could prove catastrophic if it is ignored. Since 6% of the current global oil production (including NGLs) is used to manufacture plastic commodities – predicted to rise to 20% by 2050 – the current approaches for the manufacture and use of plastics (including their end-use) demand immediate revision. More extensive collection and recycling of plastic items at the end of their life, for re-use in new production[222] to offset the use of virgin plastic, is a critical aspect both for reducing the amount of plastic waste entering the environment, and in improving the efficiency of fossil resource use. This is central to the ideology underpinning the circular economy, which has common elements with permaculture[25], the latter being a regenerative design system based on 'nature as teacher', which could help optimise the use of resources in town and city environments, while minimising and repurposing 'waste'. Thus, food might be produced more on the local than the global scale, with smaller inputs of fossil resources, water and fertilisers, and with a marked reduction in the use of plastic packaging. In addition to the greater preservation of the soil quality than is the case on industrialised farms, the more food that is grown locally, the less needs to be imported from across the country and indeed the wider world, thus saving on oil, mainly for transportation fuels, but also in the construction of vehicles themselves, according to a statistic that 15% of an average car and 50% of a Boeing Dreamliner aeroplane are made from plastics[223]. It has been estimated that just 30% of the global urban area would be required to produce all the vegetables consumed by urban dwellers[25]. Such an approach taken by billions of individuals could prove of immense significance in ensuring future food security, and in reducing waste and pollution – of all kinds.

In summary, it is the integrated issue of how we use our resources that must concern us, as can only be addressed with a 'systems thinking' approach. Since the majority of the global population lives in towns and cities, it will be necessary to incorporate integrated ('systems') design approaches such as permaculture, and the circular economy within the existing urban infrastructure. In regard to our use of plastics, and the fossil resources more generally, it is clear that only by moving from the current linear, 'take, make, dispose (waste-creation)' model for resource consumption, to the systemic, circular alternative of 'reduce, reuse, recycle, regenerate', are we likely to 'care for our common home', and establish a viable future course for humanity.

12. References

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