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REVIEW ARTICLE

Buy-now-pay-later: Hazards to human and planetary health from plastics production, use and waste

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More than 8 billion tonnes of plastic were produced between 1950 and 2015, that is 1 tonne for every man, woman and child on our planet. Global plastic production has been growing exponentially with an annual growth rate of 8.4% since 1950, equating to approximately 380 million tonnes per annum. A further 50 kg of plastic is now being produced for each person every year with production continuing to accelerate. Here, we discuss the human and planetary health hazards of all that plastic. We consider each step in the journey of these complex and pervasive industrial materials: from their synthesis predominantly from fossil fuel feedstocks, through an often-brief consumer use as plastic products, and onto waste streams as fuel, permanent landfill or as unmanaged waste in our environment, food, air and bodies.

Key words: environment; environmental pollution; public health; population health; plastics; polymers.

Hazards of Plastic Production

What are plastics?

Consumer plastics are highly complex industrial materials, incorporating a polymer matrix mixed with a diverse array of additives and processing agents, plus impurities, by-products, breakdown products and contaminants.[1,2] More than 10 500 monomers, additives and processing agents are registered for production internationally, with nearly 40% produced at high volumes[2] at a total of 25 million tonnes annually.[1] Additives comprise approximately 7% of plastic products by weight,[1] and include plasticisers, flame retardants, antioxidants, UV stabilisers and pigments that are mixed with the polymer to produce specific products,[1–3] or as fillers.[1] Additives are not typically bonded to the polymer and leach out over time and with use.[3–5]

Key Points

1. Global plastic production has been growing and has diverse and concerning effects on human and planetary health.
2. As consumers, we can ask where the plastic comes from, what is in it, and where it goes.
3. As health professionals, we can educate ourselves about the harms of plastic, and advocate for recyclable, safer plastic to rescue the health of future generations and of the planet.

Raw materials

While plastic waste is a visible environmental problem, there is less consumer awareness of the significant environmental impact of plastic production.[6–8] Plastic polymers and additives are overwhelmingly synthesised from 'virgin' petrochemicals. Plastic production starts with the extraction, transport and refinement of crude oil, with environmental damage at the site of extraction, risk of crude-oil spillage during extraction and transportation, contamination of groundwater due to fracking, and air pollution from flaring (burning off excess gasses at extraction), transportation emissions and refinement[9,10] (Fig. 1).

Manufacture

Refined petrochemicals such as ethylene, propylene or benzene are used to synthesise plastic monomers, which are bonded together as polymers. Similar to refinement, this is energy-intensive and produces significant amounts of carbon dioxide.[9] Additionally, the vast majority of these processes use hazardous chemicals, including the monomers themselves (such as propylene, styrene, vinyl chloride and butadiene), intermediates in monomer production (such as benzene and toluene), processing agents and by-products.[9] Additives follow a similar process of chemical synthesis through multiple intermediates. These pose occupational as well as environmental hazards, through emission

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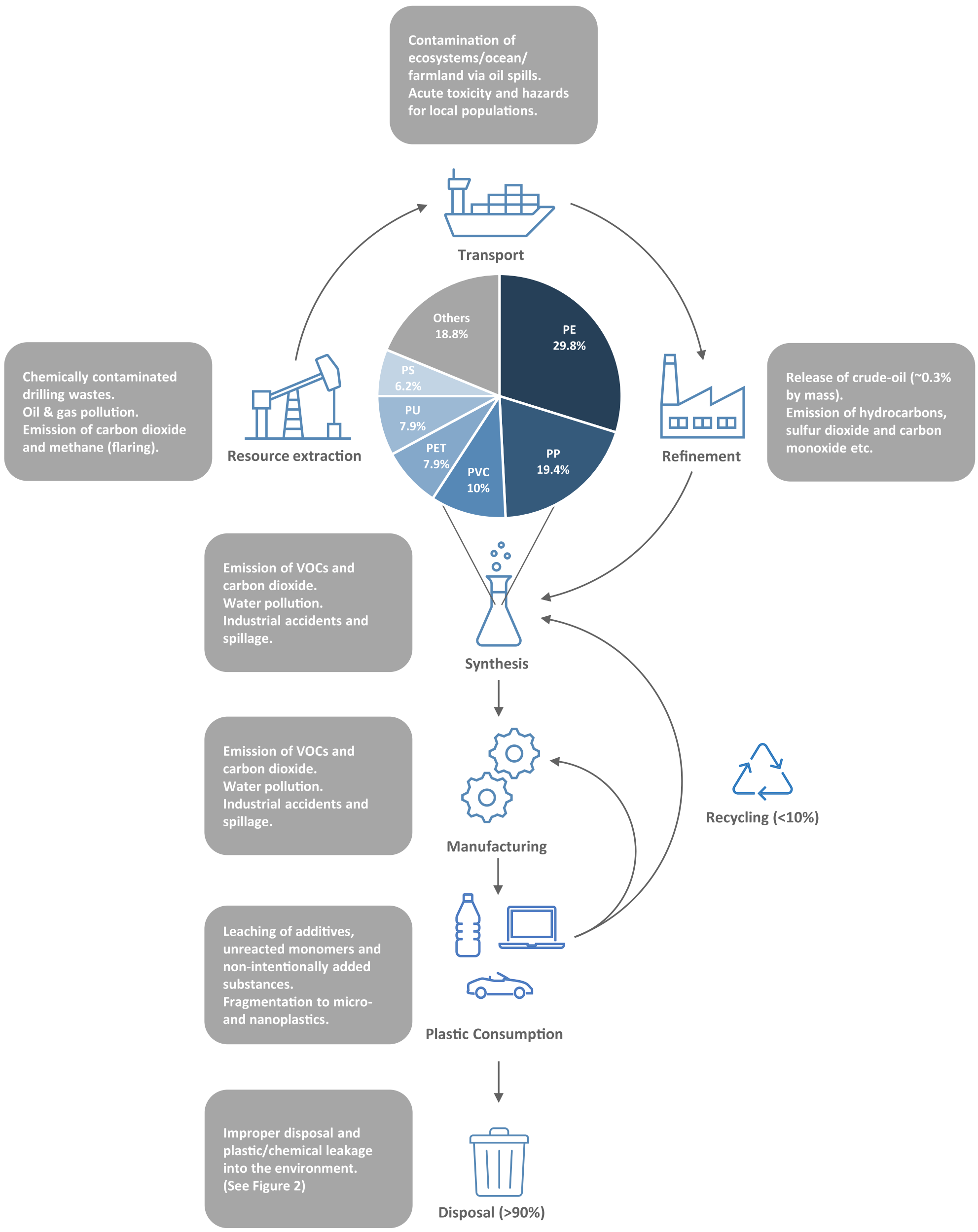

Fig. 1 Plastic supply chain and potential hazards for planetary and human health and share of main polymers for plastic production. PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; PU, polyurethanes; PVC, polyvinyl chloride; VOCs = volatile organic compounds.

of gases/vapours, contamination of waterways or soils by chemical waste mismanagement, or through industrial accidents[9] (Figs 1, 2).

For example, antimony is used as a catalyst during monomer synthesis and remains in the process stream during polymerisation and manufacturing of, for example, drinking bottles and textiles. Insufficient wastewater treatment or leaching from plastic products leads to antinomy pollution of rivers near polyethylene terephthalate production sites which threatens local drinking water supplies.[11]

Human health implications of plastic production

Environmental hazards of plastic production affect human health directly and indirectly (Fig. 3). The contribution of plastics production to both global carbon emissions and particulate air pollution is of growing concern. Throughout the supply chain, plastic contributes approximately 4% of total global greenhouse emissions.[12] Urgent changes to global emissions are critical to avoid a disastrous 1.5°C increase in anthropogenic warming.[13] The human health effects of climate change alone are profound, and

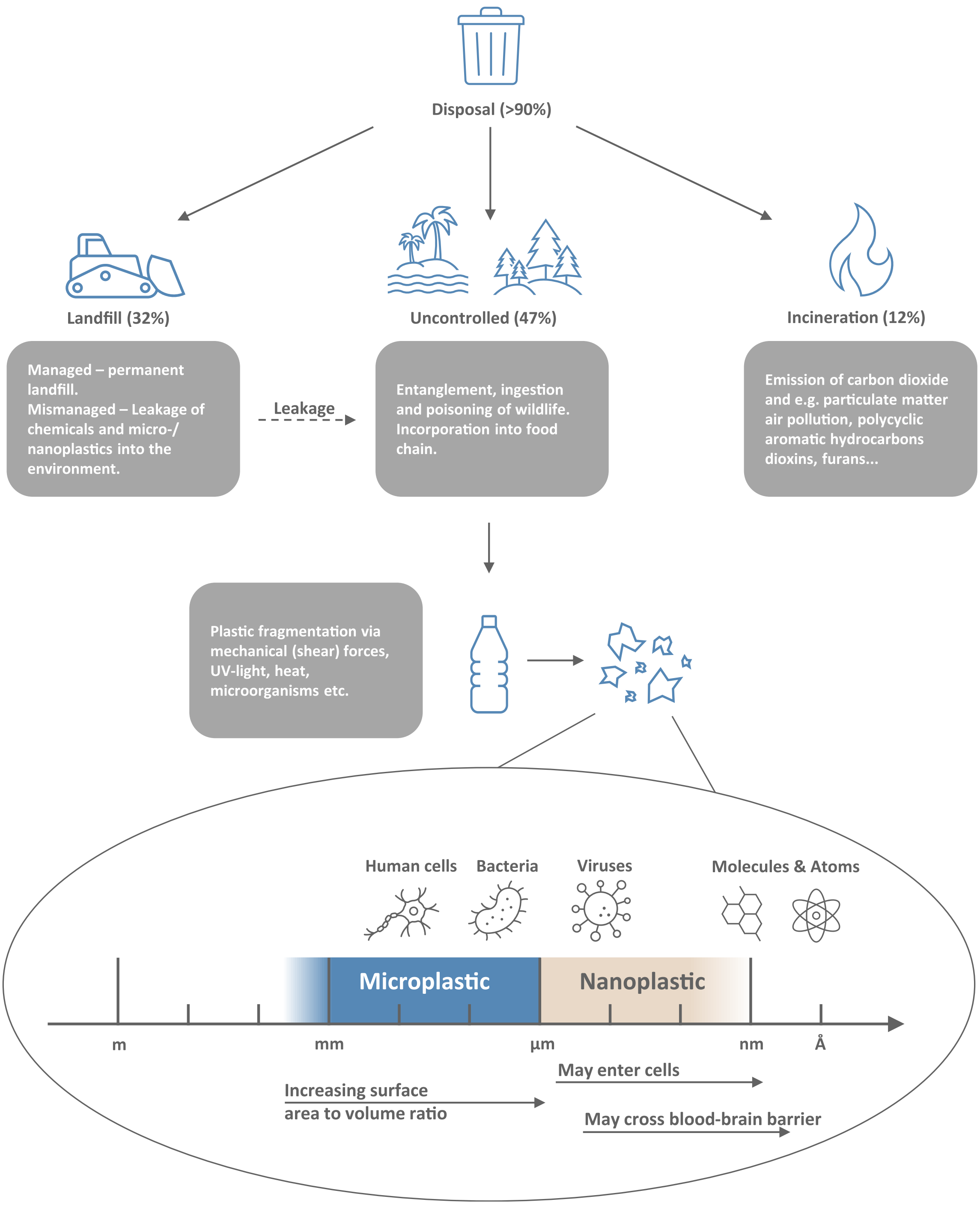

Fig. 2 Potential hazards for planetary and human health from different forms of plastic disposal (top) and fragmentation of plastic products into micro- and nanoplastics (bottom).

already being felt.[14] Outdoor fine particulate matter ($PM_{2.5}$) – such as produced during flaring, from transportation diesel and in crude oil refinement – is the fifth leading death risk factor world-wide[15] and underscores the risk of such a large-scale industry dependent on petrochemical feedstock.

Hazards of Plastic Use

The next step in the plastic supply chain is the use of manufactured plastic products, the largest markets being packaging (38%), building and construction (16%) and textiles (15%),[1] but

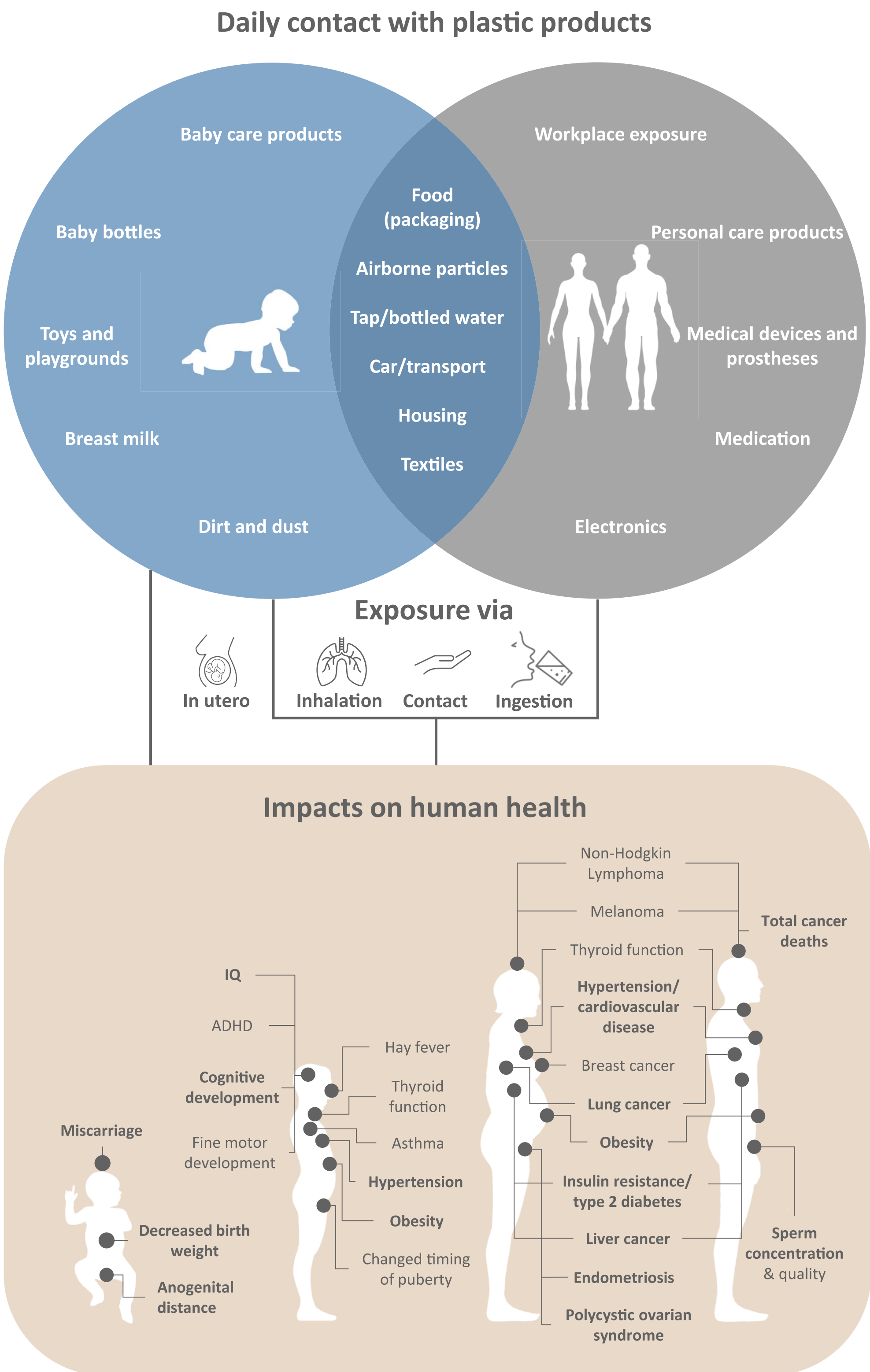

Fig. 3 Common routes of plastic exposure for children and adults (top) and impacts on human health based on systematic review with meta-analysis (bottom). See text for references.

with diverse applications across almost every aspect of our lives (Fig. 3). The volumes at which plastics are produced reflect a growing dependence on these products including household goods, food processing and packaging, personal care products and medical applications, both external and internal. In each application, including food packaging,[4] we are exposed to a complex mixture of chemicals. With use, degradation products are also formed and plastic itself fragments to micro- and nanoplastics (Fig. 3).

The primary hazard during direct consumer exposure to plastic is chemicals that leach out from the plastic,[3–5] and which may enter food and drink during processing or from packaging. Some of the smallest and most volatile chemicals can also be absorbed transdermally or dispersed into the air and inhaled (in each case bypassing first-pass metabolism). Young children have additional exposure through oral exploratory behaviour and/or non-nutritional ingestion, including their toys and accumulated chemicals in household dust and soil.

For the vast majority of plastic additives, we know little about the degree of human exposure or possible human health impacts. There are limitations of *in vitro* and animal studies to evaluate effects of low-dose, long-term human exposure, and there is no systematic process for post-marketing surveillance, as there is for pharmaceuticals or pesticides. This issue is compounded for non-intentionally added substances where identity is unknown or not disclosed.[4] Indeed, of approximately 10 500 known plastic monomers, chemical additives and processing aids, approximately 4100 lack any reported hazard classifications.[2] Of the 6436 chemicals for which hazard data are available, 3950 have been identified as substances of low concern; of the remaining 2486 chemicals, 1232 are of medium concern and 1254 are of high concern.[2]

Knowledge of direct human health effects is limited to a small subset where techniques have been independently developed to measure the chemical or its metabolites in human biosamples, and observational studies have then evaluated the association between individual exposure and health outcomes. Examples include certain bisphenol monomers, phthalate plasticisers, organohalide flame retardants and polyfluoroalkyl processing aids. The key findings evaluated by meta-analysis of multiple individual study populations are summarised in Figure 3.

Bisphenols

Bisphenols are used to make polycarbonates and epoxy resins, including plastic food and beverage containers or their linings. Bisphenol A (BPA) has attracted the most research with adverse associations including: anogenital distance in newborn girls,[16] hypertension,[17] cardiovascular disease,[18] polycystic ovary syndrome,[19] insulin resistance,[20] type 2 diabetes,[17,21,22] obesity and increased waist circumference.[17,21,22] There are no global treaties relating to BPA or other bisphenols; regulations vary from country to country. Driven by consumer pressure, industry has reduced BPA use but BPA has largely been replaced by other bisphenols with very similar biological activity *in vitro* and in animal studies.[23]

Phthalates (ortho-phthalate diesters)

Phthalates are the main plasticisers used to increase the flexibility of plastics. Exposure is usually measured as a metabolite in urine. Adverse associations include: miscarriage,[24] anogenital distance in newborn boys[25] and sperm concentration.[26] Additional concerns for harm, but with differing findings for different phthalates, include birthweight in newborns,[27] asthma,[28,29] psychomotor development,[30] cognitive development and IQ,[30] precocious puberty in girls,[31,32] increased blood pressure in children,[27] insulin resistance,[20,33] type 2 diabetes,[20] thyroid function,[34] obesity and waist circumference,[21,27] endometriosis[35] and additional sperm quality measures.[26] There are no global treaties relating to phthalates.

Halogenated flame retardants

Halogenated flame retardants used in plastics include polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs). Adverse health effects associated with PCBs include: reduced birthweight,[36,37] death from certain cancers,[38,39] cardiovascular disease,[18] type 2 diabetes[20,40] and endometriosis.[41,42] Adverse health effects associated with PBDEs include: reduced birthweight,[43] cognitive development and IQ.[44] Additional concerns include: insulin resistance,[20] infant bronchitis,[45] several cancers[38,39,42,46–49] for PCBs and thyroid function[17] for PBDEs. PCBs and certain PBDEs are regulated under the Stockholm Convention as Persistent Organic Pollutants (POPs), but replacements include other brominated flame retardants, some with strong structural similarities.

Per- and polyfluoroalkyl substances

Per- and polyfluoroalkyl substances (PFAS) are used in firefighting foams, as protective coatings for food packaging, textiles and furniture, but also in the manufacture of fluoropolymer plastics for non-stick cookware and waterproof fabrics. There are more than 9000 PFAS,[50] but only a handful have been studied for human exposure and health effects. Adverse health effects associated with PFAS include: decreased birthweight and length in newborns[51–53] and obesity in children.[54] Additional concerns include: neurodevelopment,[55] allergic rhinitis in children[56] and thyroid function.[57] Some PFAS are regulated under the Stockholm Convention as POPs, but otherwise regulation varies from country to country.

Other monomers, additives, processing aids and non-intentionally added substances

The small number of chemicals studied across the above categories only captures a tiny fraction of over 10 500 chemicals in plastics,[2] leaving considerable uncertainty regarding health effects of other high-volume production additives. 'Non-targeted' approaches to identify other chemicals leaching from consumer products,[58,59] in food,[60] household environmental samples,[61] or indeed in human biospecimens,[62,63] are starting to identify a much more extensive range of plastic chemical exposure, including organophosphate flame retardants, UV filters and stabilisers and non-phthalate plasticisers,[58–63] for which human health effects are unknown.

Hazards of Plastic Waste

Waste streams and recycling

Global plastic waste management has lagged behind waste production with only approximately 9% being recycled.[1] Traditional mechanical recycling methods largely yield down-cycled plastic of inferior quality, more limited application and reduced recycling options.[64] Emerging chemical recycling technologies provide potential recycling of the same plastic,[65,66] but need further development to address high cost and energy requirements. A greater proportion (12%) is incinerated in purpose-built facilities. This provides an option for lower grade non-recyclable plastic, but releases the embedded carbon as carbon dioxide. In the absence of controlled incineration, open burns are common, releasing toxic airborne pollutants alongside embedded carbon.[67] The vast majority (79%) of plastic waste is discarded.[1] Even in the best-case scenario, processing and landfill results in accumulation because anaerobic conditions limit degradation.[68] Of all plastics produced annually, nearly half is mismanaged,[69] with littering or leaking from landfills resulting in pollution of land, freshwater waterways and the ocean.[70]

Macro, micro- and nanoplastic waste

The visible components of plastic waste are macroplastics including plastic products that retain sufficient integrity to be recognisable and initial fragmentation products. Progressive weathering and fragmentation lead to ever smaller fragments, namely microplastics (<5 mm)[71] and nanoplastics (typically defined either as <1 μm or <100 nm).[5,71]

Macroplastics present certain physical hazards to humans such as injury and substantive hazards to marine life.[72] There is strong public awareness of these environmental hazards, especially for marine life, but less so of micro- and nanoplastics.[6,7]

Micro- and nanoplastics present very different hazards, with four key areas of concern being: leaching of additives; plastic particles as vectors for environmental contaminants and microorganisms; indirect effects through actions at the lining of our guts or lungs; and, for particles small enough to pass through biological barriers, direct effects within tissues.

In addition to degradation of waste macroplastics, micro- and nanoplastics are also intentionally added, for example as abrasives in personal care products,[73–76] or released from plastic products during daily use, including synthetic clothing,[73,75,77] plastic food containers and even baby bottles.[78] Most research has focused on larger microplastics >10 μm that are visible with microscopy techniques. There are concerning knowledge gaps regarding nanoplastics which, because of their smaller size, are anticipated to pose greater hazards for human toxicity.[5] The smallest microplastics (<10 μm) and nanoplastics are too small to detect with microscopy techniques used for larger microplastics, and their small size poses additional analytical challenges,[5] with techniques only beginning to emerge.

Human exposure

Microplastics have been detected in almost every part of the environment,[75,76,79] including freshwater and air,[73,75,76] in drinking water and a diverse range of foods and beverages including honey, milk, seafood, table salt and beer.[73–75]

Ingestion and local effects in the gut

Estimates of microplastic ingested are imprecise, but could be as high as approximately 200 000 microplastic particles/day or 0.1–5 g/week.[80] Microplastics are present in stools of humans and also many animals.[81] Animal studies have reported multiple local effects of engineered nano- and microplastics in the gut, including inflammation, barrier function deterioration and gut microbiota changes.[76]

Inhalation and local effects in the lung

Airborne microplastics are prevalent even in very remote planetary regions.[82] Inhalation of airborne microplastics is modelled to be a major route of human exposure,[73,83] with evidence for plastic fibres in human lung tissue.[82,84] There are multiple sources of airborne microplastics including microplastic fibres from synthetic textiles and the synthetic textile industry[82,83] and microplastic degradation products from vehicle tyres.[82] 'Tyre crumb' alone is a substantive component of overall $PM_{2.5}$ and PM_{10} particulate air pollution,[82] although the overall contribution of microplastics is unknown.[82]

Occupationally exposed textile workers may experience a range of interstitial lung disease[82,83]: lung biopsies reveal inflammation, fibrosis and granuloma formation.[82,83] *In vitro* studies in human lung cell lines have separately reported pro-inflammatory, cytotoxic or pro-apoptotic effects of engineered nano- and microplastics.[82]

Internal exposure and detection in tissues

The likelihood of uptake of micro- and nanoplastics through gastrointestinal and alveolar epithelium differs by size.[5,73] Animal and *in vitro* models of human biological barriers show translocation of microplastics below 5–10 μm from the gut into the circulatory and/or lymphatic systems.[73,75,85] In animal models, *in vitro* and in a human placental perfusion study, engineered nanoplastics cross cell membranes as well as specialist biological barriers such as the mammalian placental barrier and blood–brain barrier.[73,75]

To date, microplastics have been detected in human faeces,[86] lung[82,84] and colectomy samples[87] as well as placenta[88,89] although the latter requires further confirmation. Techniques to directly detect nanoplastics in human tissue are yet to be established.

It is not known what the direct biological effects of micro- and nanoplastic fragments may be in the diverse tissues and organs but there is the potential, as shown in animal models and human *in vitro* studies, to disrupt fundamental processes across multiple cell types and trigger, for example, inflammation and oxidative stress.[75,85,90]

Vectors for additives, environmental toxins and micro-organisms

Not only do micro- and nanoplastics contain complex mixtures of additives and other chemicals from their initial manufacture, but there is growing evidence that once in contaminated environments, like our ocean, toxic chemicals including POPs[75,77] and heavy metals[77] accumulate through adsorption. Decreasing particle size results in increasing surface-area-to-volume ratio, providing greater opportunity for diffusion of additives from the plastic, or adsorption and subsequent release of chemicals from the environment.[5] Nanoplastics are of particular concern because the combination of available surface-area for exchange and tissue penetration due to their small size could deliver locally high doses of leached compounds.[5]

Environmental microplastics may also be coated with a biofilm or 'eco-corona',[5] of particular concern due to mixing between microplastics and human effluent in sewerage.[77] There is evidence that biofilms carry pathogenic bacteria, some with microbial resistance.[72,75,77]

Conclusion

Not simple, not cheap, not convenient, not inert and not sustainable

We need to fundamentally re-think plastics. Consumers perceive plastics to be cheap, convenient and recyclable.[7] But plastics are complex mixtures of industrial chemicals, and our review uncovers an intricate set of hazards that we poorly understand and are currently failing to manage. Not only are plastics rarely recycled to keep them out of waste streams and turn the virgin plastic production tap off, but they are also largely not recyclable with existing technology. As with other fossil fuel commodities, market forces are not factoring in the cost of managing hazards to human and planetary health, and current generations are effectively passing responsibility for the problem onto future generations who do not have a voice.

What can you do?

As consumers, we can value the full cost of the plastic we use each day, 'choose to refuse' and reduce use. We can be curious and ask questions about where the plastic comes from, what is in it and where it goes.

As medical professionals, we have expertise to share the science and the respected voice to advocate for the health of future generations and the planet that they depend on. We can use that voice to advocate with regulators so that industry takes responsibility for the hazards of their products, and to empower consumers to demand this of industry, regulators and brands.

Opportunity for change

Change is possible. Plastics can be simpler, safer and recyclable. This will require improved recycling technology to turn off the tap on virgin plastic,[91] redesign of the plastics themselves and redesign plastic chemical regulation. Working with industry to introduce extended producer responsibility for plastic use and waste management will require intervention by policy-makers to reduce demand for plastics, for example by banning unnecessary plastic applications, and to level the economic playfield for sustainable circular plastic, for example by taxing virgin fossil fuel-based feedstocks and introducing minimum recycled content standards. A mechanism for post-marketing surveillance, just as with pharmaceuticals or pesticides, is also critical. We should not be producing vast quantities of chemicals of unknown human toxicity if we cannot detect human exposure nor monitor health effects. Transparency around additives and non-intentionally added substances in plastics is therefore essential, as are methods for detecting plastic chemicals in ongoing biomonitoring programmes. Investment in techniques to measure nanoplastics and study their health effects is also critical.

Change is starting. Global bodies such as the Organisation for Economic Co-operation and Development are reviewing our relationship with plastics,[92] as are influential regional regulatory bodies such as the European Union.[93,94] Canada has defined plastics as toxic,[95] acknowledging the environmental impact of plastic and its harm to human health. Adding the authoritative voice of medical professions to advocate for the health of future generations is a critical element that adds weight to the urgent need to regulate and redesign plastic.

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Rapunzel's dream view by Julia Mathyi (10y) from Book Covers exhibition, Children's Hospital at Westmead