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Review

Plastics, the environment and human health: current consensus and future trends

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Plastics have transformed everyday life; usage is increasing and annual production is likely to exceed 300 million tonnes by 2010. In this concluding paper to the Theme Issue on Plastics, the Environment and Human Health, we synthesize current understanding of the benefits and concerns surrounding the use of plastics and look to future priorities, challenges and opportunities. It is evident that plastics bring many societal benefits and offer future technological and medical advances. However, concerns about usage and disposal are diverse and include accumulation of waste in landfills and in natural habitats, physical problems for wildlife resulting from ingestion or entanglement in plastic, the leaching of chemicals from plastic products and the potential for plastics to transfer chemicals to wildlife and humans. However, perhaps the most important overriding concern, which is implicit throughout this volume, is that our current usage is not sustainable. Around 4 per cent of world oil production is used as a feedstock to make plastics and a similar amount is used as energy in the process. Yet over a third of current production is used to make items of packaging, which are then rapidly discarded. Given our declining reserves of fossil fuels, and finite capacity for disposal of waste to landfill, this linear use of hydrocarbons, via packaging and other short-lived applications of plastic, is simply not sustainable. There are solutions, including material reduction, design for end-of-life recyclability, increased recycling capacity, development of bio-based feedstocks, strategies to reduce littering, the application of green chemistry life-cycle analyses and revised risk assessment approaches. Such measures will be most effective through the combined actions of the public, industry, scientists and policymakers. There is some urgency, as the quantity of plastics produced in the first 10 years of the current century is likely to approach the quantity produced in the entire century that preceded.

Keywords: plastic; polymer; debris; endocrine disruption; phthalates; waste management

1. INTRODUCTION

Many of the current applications and the predicted benefits of plastic follow those outlined by Yarsley and Couzens in the 1940s. Their account of the benefits that plastics would bring to a person born nearly 70 years ago, at the beginning of this '*plastic age*', was told with much optimism:

> It is a world free from moth and rust and full of colour, a world largely built up of synthetic materials made from the most universally distributed substances, a world in which nations are more and more independent of localised naturalised resources, a world in which man, like a magician, makes what he wants for almost every need out of what is beneath and around him (Yarsley & Couzens 1945, p. 152).

The durability of plastics and their potential for diverse applications, including widespread use as disposable items, were anticipated, but the problems associated with waste management and plastic debris were not. In fact the predictions were '*how much brighter and cleaner a world* [it would be] *than that which preceded this plastic age*' (Yarsley & Couzens 1945, p. 152).

This paper synthesizes current understanding of the benefits and concerns surrounding the use of plastics and looks to challenges, opportunities and priorities for the future. The content draws upon papers submitted to this Theme Issue on Plastics, the Environment and Human Health together with other sources. While selected citations are given to original sources of information, we primarily refer the reader to the discussion of a particular topic, and the associated references, in the Theme Issue papers. Here, we consider the subject from seven perspectives: plastics as materials; accumulation of plastic waste in the natural environment; effects of plastic debris in the

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environment and on wildlife; effects on humans; production, usage, disposal and waste management solutions; biopolymers, degradable and biodegradable polymer solutions; and policy measures.

2. PLASTICS AS MATERIALS: AN OVERVIEW

Plastics are inexpensive, lightweight, strong, durable, corrosion-resistant materials, with high thermal and electrical insulation properties. The diversity of polymers and the versatility of their properties are used to make a vast array of products that bring medical and technological advances, energy savings and numerous other societal benefits (Andrady & Neal 2009). As a consequence, the production of plastics has increased substantially over the last 60 years from around 0.5 million tonnes in 1950 to over 260 million tonnes today. In Europe alone the plastics industry has a turnover in excess of 300 million euros and employs 1.6 million people (Plastics Europe 2008). Almost all aspects of daily life involve plastics, in transport, telecommunications, clothing, footwear and as packaging materials that facilitate the transport of a wide range of food, drink and other goods. There is considerable potential for new applications of plastics that will bring benefits in the future, for example as novel medical applications, in the generation of renewable energy and by reducing energy used in transport (Andrady & Neal 2009).

Virgin plastic polymers are rarely used by themselves and typically the polymer resins are mixed with various additives to improve performance. These additives include inorganic fillers such as carbon and silica that reinforce the material, plasticizers to render the material pliable, thermal and ultraviolet stabilizers, flame retardants and colourings. Many such additives are used in substantial quantities and in a wide range of products (Meeker *et al.* 2009). Some additive chemicals are potentially toxic (for example lead and tributyl tin in polyvinyl chloride, PVC), but there is considerable controversy about the extent to which additives released from plastic products (such as phthalates and bisphenol A, BPA) have adverse effects in animal or human populations. The central issue here is relating the types and quantities of additives present in plastics to uptake and accumulation by living organisms (Andrady & Neal 2009; Koch & Calafat 2009; Meeker *et al.* 2009; Oehlmann *et al.* 2009; Talsness *et al.* 2009; Wagner & Oehlmann 2009). Additives of particular concern are phthalate plasticizers, BPA, brominated flame retardants and anti-microbial agents. BPA and phthalates are found in many mass produced products including medical devices, food packaging, perfumes, cosmetics, toys, flooring materials, computers and CDs and can represent a significant content of the plastic. For instance, phthalates can constitute a substantial proportion, by weight, of PVC (Oehlmann *et al.* 2009), while BPA is the monomer used for production of polycarbonate plastics as well as an additive used for production of PVC. Phthalates can leach out of products because they are not chemically bound to the plastic matrix, and they have attracted particular attention because of their high production volumes and wide usage (Wagner & Oehlmann 2009; Talsness *et al.* 2009). Phthalates and BPA are detectable in aquatic environments, in dust and, because of their volatility, in air (Rudel *et al.* 2001, 2003). There is considerable concern about the adverse effects of these chemicals on wildlife and humans (Meeker *et al.* 2009; Oehlmann *et al.* 2009). In addition to the reliance on finite resources for plastic production, and concerns about additive effects of different chemicals, current patterns of usage are generating global waste management problems. Barnes *et al.* (2009) show that plastic wastes, including packaging, electrical equipment and plastics from end-of-life vehicles, are major components of both household and industrial wastes; our capacity for disposal of waste to landfill is finite and in some locations landfills are at, or are rapidly approaching, capacity (Defra *et al.* 2006). So from several perspectives it would seem that our current use and disposal of plastics is the cause for concern (Barnes *et al.* 2009; Hopewell *et al.* 2009).

3. ACCUMULATION OF PLASTIC WASTE IN THE NATURAL ENVIRONMENT

Substantial quantities of plastic have accumulated in the natural environment and in landfills. Around 10 per cent by weight of the municipal waste stream is plastic (Barnes *et al.* 2009) and this will be considered later in §6. Discarded plastic also contaminates a wide range of natural terrestrial, freshwater and marine habitats, with newspaper accounts of plastic debris on even some of the highest mountains. There are also some data on littering in the urban environment (for example compiled by EnCams in the UK; http://www.encams.org/home); however, by comparison with the marine environment, there is a distinct lack of data on the accumulation of plastic debris in natural terrestrial and freshwater habitats. There are accounts of inadvertent contamination of soils with small plastic fragments as a consequence of spreading sewage sludge (Zubris & Richards 2005), of fragments of plastic and glass contaminating compost prepared from municipal solid waste (Brinton 2005) and of plastic being carried into streams, rivers and ultimately the sea with rain water and flood events (Thompson *et al.* 2005). However, there is a clear need for more research on the quantities and effects of plastic debris in natural terrestrial habitats, on agricultural land and in freshwaters. Inevitably, therefore, much of the evidence presented here is from the marine environment. From the first accounts of plastic in the environment, which were reported from the carcasses of seabirds collected from shorelines in the early 1960s (Harper & Fowler 1987), the extent of the problem soon became unmistakable with plastic debris contaminating oceans from the poles to the Equator and from shorelines to the deep sea. Most polymers are buoyant in water, and since items of plastic debris such as cartons and bottles often trap air, substantial quantities of plastic debris accumulate on the sea surface and may also be washed ashore. As a consequence, plastics represent a considerable proportion (50–80%) of shoreline debris (Barnes *et al.* 2009). Quantities are highly variable in time and space, but there are reports of more than 100 000 items m^{-2} on some shorelines (Gregory 1978) and up to 3 520 000 items km^{-2} at the ocean surface (Yamashita & Tanimura 2007). Gyres and oceanic convergences appear to be particularly contaminated, as do enclosed seas such as the Mediterranean (Barnes *et al.* 2009; Ryan *et al.* 2009). Despite their buoyant nature, plastics can become fouled with marine life and sediment causing items to sink to the seabed. For example, shallow seabeds in Brazil were more heavily contaminated than the neighbouring shorelines (Oigman-Pszczol & Creed 2007), indicating that the seabed may be an ultimate sink even for initially buoyant marine debris (Barnes *et al.* 2009). In some locations around Europe, it has been suggested that quantities on the seabed may exceed 10 000 items ha^{-1}, and debris has even been reported more than a 1000 m below the ocean surface, including accounts of inverted plastic bags passing a deep-sea submersible like an assembly of ghosts (Gregory 2009). Quantitative data on the abundance of debris on the seabed are still very limited, but there are concerns that degradation rates in the deep sea will be especially slow because of darkness and cold (Barnes *et al.* 2009; Ryan *et al.* 2009).

Monitoring the abundance of debris is important to establish rates of accumulation and the effectiveness of any remediation measures. Most studies assess the abundance of all types of anthropogenic debris including data on plastics and/or plastic items as a category. In general, the abundance of debris on shorelines has been extensively monitored, in comparison to surveys from the open oceans or the seabed. In addition to recording debris, there is a need to collect data on sources; for plastic debris this should include discharges from rivers and sewers together with littering behaviour. Here, the limited data we have suggest that storm water pulses provide a major pathway for debris from the land to the sea, with 81 g m^{-3} of plastic debris during high-flow events in the USA (Ryan *et al.* 2009). Methods to monitor the abundance of anthropogenic debris (including plastics) often vary considerably between countries and organizations, adding to difficulties in interpreting trends. As a consequence, the United Nations Environment Programme and the OSPAR Commission are currently taking steps to introduce standardized protocols (OSPAR 2007; Cheshire *et al.* 2009). Some trends are evident, however, typically with an increase in the abundance of debris and fragments between the 1960s and the 1990s (Barnes *et al.* 2009). More recently, abundance at the sea surface in some regions and on some shorelines appears to be stabilizing, while in other areas such as the Pacific Gyre there are reports of considerable increases. On shorelines the quantities of debris, predominantly plastic, are greater in the Northern than in the Southern Hemisphere (Barnes 2005). The abundance of debris is greater adjacent to urban centres and on more frequented beaches and there is evidence that plastics are accumulating and becoming buried in sediments (Barnes *et al.* 2009; Ryan *et al.* 2009). Barnes *et al.* (2009) consider that contamination of remote habitats, such as the deep sea and the polar regions, is likely to increase as debris is carried there from more densely populated areas. Allowing for variability between habitats and locations, it seems inevitable, however, that the quantity of debris in the environment as a whole will continue to increase—unless we all change our practices. Even with such changes, plastic debris that is already in the environment will persist for a considerable time to come. The persistence of plastic debris and the associated environmental hazards are illustrated poignantly by Barnes *et al.* (2009) who describe debris that had originated from an aeroplane being ingested by an albatross some 60 years after the plane had crashed.

4. EFFECTS OF PLASTIC DEBRIS IN THE ENVIRONMENT AND ON WILDLIFE

There are some accounts of effects of debris from terrestrial habitats, for example ingestion by the endangered California condor, *Gymnogyps californianus* (Mee *et al.* 2007). However, the vast majority of work describing environmental consequences of plastic debris is from marine settings and more work on terrestrial and freshwater habitats is needed. Plastic debris causes aesthetic problems, and it also presents a hazard to maritime activities including fishing and tourism (Moore 2008; Gregory 2009). Discarded fishing nets result in ghost fishing that may result in losses to commercial fisheries (Moore 2008; Brown & Macfadyen 2007). Floating plastic debris can rapidly become colonized by marine organisms and since it can persist at the sea surface for substantial periods, it may subsequently facilitate the transport of non-native or 'alien' species (Barnes 2002; Barnes *et al.* 2009; Gregory 2009). However, the problems attracting most public and media attention are those resulting in ingestion and entanglement by wildlife. Over 260 species, including invertebrates, turtles, fish, seabirds and mammals, have been reported to ingest or become entangled in plastic debris, resulting in impaired movement and feeding, reduced reproductive output, lacerations, ulcers and death (Laist 1997; Derraik 2002; Gregory 2009). The limited monitoring data we have suggest rates of entanglement have increased over time (Ryan *et al.* 2009). A wide range of species with different modes of feeding including filter feeders, deposit feeders and detritivores are known to ingest plastics. However, ingestion is likely to be particularly problematic for species that specifically select plastic items because they mistake them for their food. As a consequence, the incidence of ingestion can be extremely high in some populations. For example, 95 per cent of fulmars washed ashore dead in the North Sea have plastic in their guts, with substantial quantities of plastic being reported in the guts of other birds, including albatross and prions (Gregory 2009). There are some very good data on the quantity of debris ingested by seabirds recorded from the carcasses of dead birds. This approach has been used to monitor temporal and spatial patterns in the abundance of sea-surface plastic debris on regional scales around Europe (Van Franeker *et al.* 2005; Ryan *et al.* 2009).

An area of particular concern is the abundance of small plastic fragments or microplastics. Fragments as small as 1.6 μm have been identified in some marine habitats, and it seems likely there will be even smaller pieces below current levels of detection. A recent workshop convened in the USA by the National Oceanic and Atmospheric Administration concluded that microplastics be defined as pieces <5 mm with a suggested lower size boundary of 333 μm so as to focus on microplastics that will be captured using conventional sampling approaches (Arthur *et al.* 2009). However, we consider it important that the abundance of even smaller fragments is not neglected. Plastic fragments appear to form by the mechanical and chemical deterioration of larger items. Alternative routes for microplastics to enter the environment include the direct release of small pieces of plastics that are used as abrasives in industrial and domestic cleaning applications (e.g. shot blasting or scrubbers used in proprietary hand cleansers) and spillage of plastic pellets and powders that are used as a feedstock for the manufacture of most plastic products. Data from shorelines, from the open ocean and from debris ingested by seabirds, all indicate that quantities of plastic fragments are increasing in the environment, and quantities on some shores are substantial ($>10\%$ by weight of strandline material; Barnes *et al.* 2009). Laboratory experiments have shown that small pieces such as these can be ingested by small marine invertebrates including filter feeders, deposit feeders and detritivores (Thompson *et al.* 2004), while mussels were shown to retain plastic for over 48 days (Browne *et al.* 2008). However, the extent and consequences of ingestion of microplastics by natural populations are not known.

In addition to the physical problems associated with plastic debris, there has been much speculation that, if ingested, plastic has the potential to transfer toxic substances to the food chain (see Teuten *et al.* 2009). In the marine environment, plastic debris such as pellets, fragments and microplastics have been shown to contain organic contaminants including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, petroleum hydrocarbons, organochlorine pesticides (2,2′-bis(*p*-chlorophenyl)-1,1,1 trichloroethane (DDT) and its metabolites; together with hexachlorinated hexane (HCH)), polybrominated diphenylethers (PBDEs), alkylphenols and BPA at concentrations ranging from $\mathrm{ng\,g^{-1}}$ to $\mathrm{\mu g\,g^{-1}}$. Some of these compounds are added to plastics during manufacture while others adsorb to plastic debris from the environment. Work in Japan has shown that plastics can accumulate and concentrate persistent organic pollutants that have arisen in the environment from other sources. These contaminants can become orders of magnitude more concentrated on the surface of plastic debris than in the surrounding sea water (Mato *et al.* 2001). Teuten *et al.* (2009) describe experiments to examine the transfer of these contaminants from plastics to seabirds and other animals. The potential for transport varies among contaminants, polymers and possibly also according to the state of environmental weathering of the debris. Recent mathematical modelling studies have shown that even very small quantities of plastics could facilitate transport of contaminants from plastic to organisms upon ingestion. This could present a direct and important route for the transport of chemicals to higher animals such as seabirds (Teuten *et al.* 2007, 2009), but will depend upon the nature of the habitat and the amount and type of plastics present. For instance, the extent to which the presence of plastic particles might contribute to the total burden of contaminants transferred from the environment to organisms will depend upon competitive sorption and transport by other particulates (Arthur *et al.* 2009). The abundance of fragments of plastic is increasing in the environment; these particles, especially truly microscopic fragments less than the 333 μm proposed by NOAA (see earlier), have a relatively large surface area to volume ratio that is likely to facilitate the transport of contaminants, and because of their size such fragments can be ingested by a wide range of organisms. Hence, the potential for plastics to transport and release chemicals to wildlife is an emerging area of concern.

More work will be needed to establish the full environmental relevance of plastics in the transport of contaminants to organisms living in the natural environment, and the extent to which these chemicals could then be transported along food chains. However, there is already clear evidence that chemicals associated with plastic are potentially harmful to wildlife. Data that have principally been collected using laboratory exposures are summarized by Oehlmann *et al.* (2009). These show that phthalates and BPA affect reproduction in all studied animal groups and impair development in crustaceans and amphibians. Molluscs and amphibians appear to be particularly sensitive to these compounds and biological effects have been observed in the low $\mathrm{ng\,l^{-1}}$ to $\mathrm{\mu g\,l^{-1}}$ range. In contrast, most effects in fish tend to occur at higher concentrations. Most plasticizers appear to act by interfering with hormone function, although they can do this by several mechanisms (Hu *et al.* 2009). Effects observed in the laboratory coincide with measured environmental concentrations, thus there is a very real probability that these chemicals are affecting natural populations (Oehlmann *et al.* 2009). BPA concentrations in aquatic environments vary considerably, but can reach $21\ \mathrm{\mu g\,l^{-1}}$ in freshwater systems and concentrations in sediments are generally several orders of magnitude higher than in the water column. For example, in the River Elbe, Germany, BPA was measured at $0.77\ \mathrm{\mu g\,l^{-1}}$ in water compared with $343\ \mathrm{\mu g\,kg^{-1}}$ in sediment (dry weight). These findings are in stark contrast with the European Union environmental risk assessment predicted environmental concentrations of $0.12\ \mathrm{\mu g\,l^{-1}}$ for water and $1.6\ \mathrm{\mu g\,kg^{-1}}$ (dry weight) for sediments.

Phthalates and BPA can bioaccumulate in organisms, but there is much variability between species and individuals according to the type of plasticizer and experimental protocol. However, concentration factors are generally higher for invertebrates than vertebrates, and can be especially high in some species of molluscs and crustaceans. While there is clear evidence that these chemicals have adverse effects at environmentally relevant concentrations in laboratory studies, there is a need for further research to establish population-level effects in the natural environment (see discussion in Oehlmann *et al.* 2009), to establish the long-term effects of exposures (particularly due to exposure of embryos), to determine effects of exposure to contaminant mixtures and to establish the role of plastics as sources (albeit not exclusive sources) of these contaminants (see Meeker *et al.* (2009) for discussion of sources and routes of exposure).

5. EFFECTS ON HUMANS: EPIDEMIOLOGICAL AND EXPERIMENTAL EVIDENCE

Turning to adverse effects of plastic on the human population, there is a growing body of literature on potential health risks. A range of chemicals that are used in the manufacture of plastics are known to be toxic. Biomonitoring (e.g. measuring concentration of environmental contaminants in human tissue) provides an integrated measure of an organism's exposure to contaminants from multiple sources. This approach has shown that chemicals used in the manufacture of plastics are present in the human population, and studies using laboratory animals as model organisms indicate potential adverse health effects of these chemicals (Talsness *et al.* 2009). Body burdens of chemicals that are used in plastic manufacture have also been correlated with adverse effects in the human population, including reproductive abnormalities (e.g. Swan *et al.* 2005; Swan 2008; Lang *et al.* 2008).

Interpreting biomonitoring data is complex, and a key task is to set information into perspective with dose levels that are considered toxic on the basis of experimental studies in laboratory animals. The concept of 'toxicity' and thus the experimental methods for studying the health impacts of the chemicals in plastic, and other chemicals classified as endocrine disruptors, is currently undergoing a transformation (a paradigm inversion) since the disruption of endocrine regulatory systems requires approaches very different from the study of acute toxicants or poisons. There is thus extensive evidence that traditional toxicological approaches are inadequate for revealing outcomes such as 'reprogramming' of the molecular systems in cells as a result of exposure to very low doses during critical periods in development (e.g. Myers *et al.* 2009). Research on experimental animals informs epidemiologists about the potential for adverse effects in humans and thus plays a critical role in chemical risk assessments. A key conclusion from the paper by Talsness *et al.* (2009) is the need to modify our approach to chemical testing for risk assessment. As noted by these authors and others, there is a need to integrate concepts of endocrinology in the assumptions underlying chemical risk assessment. In particular, the assumptions that dose–response curves are monotonic and that there are threshold doses (safe levels) are not true for either endogenous hormones or for chemicals with hormonal activity (which includes many chemicals used in plastics) (Talsness *et al.* 2009).

The biomonitoring approach has demonstrated phthalates and BPA, as well as other additives in plastics and their metabolites, are present in the human population. It has also demonstrated that the most common human exposure scenario is to a large number of these chemicals simultaneously. These data indicate differences according to geographical location and age, with greater concentrations of some of these chemicals in young children. While exposure via house dust is extensive (Rudel *et al.* 2008), it would appear that at least for some phthalates (e.g. diethylhexyl phthalate, DEHP), foodstuffs and to a lesser extent use of oral drugs probably present major uptake pathways (Wormuth *et al.* 2006). Exposure data for BPA are similar but less extensive. While average concentrations of phthalates in selected populations worldwide appear quite similar, there is evidence of considerable variability in daily intake rates among individuals, and even within individuals (Peck *et al.* 2009). Exposures through ingestion, inhalation and dermal contact are all considered important routes of exposure for the general population (Adibi *et al.* 2003; Rudel *et al.* 2003). Koch & Calafat (2009) show that while mean/median exposures for the general population were below levels determined to be safe for daily exposure (USA, EPA reference dose, RfD; and European Union tolerable daily intake, TDI), the upper percentiles of di-butyl phthalate and DEHP urinary metabolite concentrations show that for some people daily intake might be substantially higher than previously assumed and could exceed estimated safe daily exposure levels. Current 'safe' exposure levels are typically based on the application of traditional toxicological assumptions regarding acute toxicants to calculate daily exposures for chemicals in a range of widely used plastic items. The toxicological consequences of such exposures, especially for susceptible subpopulations such as children and pregnant women, remain unclear and warrant further investigation. However, there is evidence of associations between urinary concentrations of some phthalate metabolites and biological outcomes (Swan *et al.* 2005; Swan 2008). For example, an inverse relationship has been reported between the concentrations of DEHP metabolites in the mother's urine and anogenital distance, penile width and testicular decent in male offspring (Swan *et al.* 2005; Swan 2008). In adults, there is some evidence of a negative association between phthalate metabolites and semen quality (Meeker & Sathyanarayana) and between high exposures to phthalates (workers producing PVC flooring) and free testosterone levels. Moreover, recent work (Lang *et al.* 2008) has shown a significant relationship between urine levels of BPA and cardiovascular disease, type 2 diabetes and abnormalities in liver enzymes, and Stahlhut *et al.* (2009) have reported that exposure of adults in the USA to BPA is likely to occur from multiple sources and that the half-life of BPA is longer than previously estimated, and the very high exposure of premature infants in neonatal intensive-care units to both BPA and phthalates is of great concern (Calafat *et al.* 2009). These data indicate detrimental effects in the general population may be caused by chronic low-dose exposures (separately or in combination) and acute exposure to higher doses, but the full extent to which chemicals are transported to the human population by plastics is yet to be confirmed.

Much has been learned about toxicological effects on humans from experiments using laboratory animals. This approach has been used to examine component chemicals used in plastic production. A summary of work on phthalates, BPA and tetrabromobisphenol A (TBBPA) is presented by Talsness *et al.* (2009). The male reproductive tract is particularly sensitive to phthalate exposure. However, most reproductive effects are not exerted by phthalate diesters themselves, but by their monoester metabolites, which are formed in the liver. The majority of these studies have been done using rats as a model organism, with doses at least an order of magnitude higher than those to which humans are commonly exposed, but they have resulted in rapid, severe changes in the rat testis. Reproductive effects have also been described in mice and guinea pigs. Effects on pre- and early post-natal development are of particular concern, and recent animal studies have shown exposures to certain phthalates can result in severe disorders of the developing male reproductive system. It should be noted that most work on animals has used phthalate exposures much higher than estimated daily human exposures (see above), and researchers have only recently started to investigate possible biological effects within the range of median human phthalate exposure (Talsness *et al.* 2009). This is of critical importance because epidemiological studies have reported associations between phthalate levels and a number of adverse health effects in humans (Swan *et al.* 2005), suggesting that either humans are more sensitive to phthalates than experimental animals or that the testing paradigm used in traditional toxicological studies, which examines one phthalate at a time, has not served to accurately predict adverse effects from the mixture of phthalates to which humans are exposed (Andrade *et al.* 2006; NAS 2008).

For BPA, there is an extensive published literature showing adverse effects of exposure at very low doses, based on administration during development and to adult experimental animals. In particular, unlike the case for experimental animal research on phthalates, there are now hundreds of experiments on laboratory animals using doses within the range of human exposures (Vandenberg *et al.* 2007). The rate and extent to which BPA is metabolized affect the interpretation of these findings, but even very low doses of BPA have been shown to cause significant stimulation of insulin secretion followed by insulin resistance in mice, a significant decrease in sperm production by rats, a decrease in maternal behaviour in mice and disruption of hippocampal synapses, leading to the appearance of a brain typical of that seen in senility in both rats and monkeys. The greatest concerns with exposure to BPA are during development; BPA appears to affect brain development leading to loss of sex differentiation in brain structures and behaviour (Talsness *et al.* 2009). A further important observation regarding adverse responses to developmental exposures of animals to very low doses of BPA is that many relate to disease trends in humans. Less has been published on effects of the flame retardant TBBPA, but there is evidence of effects on thyroid hormones, pituitary function and reproductive success in animals (Talsness *et al.* 2009).

Despite the environmental concerns about some of the chemicals used in plastic manufacture, it is important to emphasize that evidence for effects in humans is still limited and there is a need for further research and in particular, for longitudinal studies to examine temporal relationships with chemicals that leach out of plastics (Adibi *et al.* 2008). In addition, the traditional approach to studying the toxicity of chemicals has been to focus only on exposure to individual chemicals in relation to disease or abnormalities. However, because of the complex integrated nature of the endocrine system, it is critical that future studies involving endocrine-disrupting chemicals that leach from plastic products focus on mixtures of chemicals to which people are exposed when they use common household products. For example, in a study conducted in the USA, 80 per cent of babies were exposed to measurable levels of at least nine different phthalate metabolites (Sathyanarayana *et al.* 2008), and the health impacts of the cumulative exposure to these chemicals need to be determined. An initial attempt at examining more than one phthalate as a contributor to abnormal genital development in babies has shown the importance of this approach (Swan 2008). Studies of mixtures of chemicals therefore also need to extend beyond mixtures of the same class of chemical, such as mixtures of different phthalates or of different PCBs. For example, PVC (used in a wide range of products in the home including water pipes) may contain phthalates, BPA, flame retardants such as PBDEs or TBBPA, cadmium, lead and organotins, all of which have been shown in animal studies to result in obesity (Heindel & vom Saal 2009). In addition, the monomer used to manufacture PVC plastic, vinyl chloride, is a known carcinogen and exposure can cause angiosarcoma of the liver among factory workers (Bolt 2005; Gennaro *et al.* 2008). PVC in medical tubing has also been shown to be a source of high DEHP exposure among infants in neonatal intensive-care nurseries (Green *et al.* 2005) and probably contributes to the high levels of BPA found in these babies since BPA is an additive in PVC plastic (Calafat *et al.* 2009).

Examining the relationship between plastic additives and adverse human effects presents a number of challenges. In particular, the changing patterns of production and use of both plastics, and the additives they contain, as well as the confidential nature of industrial specifications makes exposure assessment particularly difficult. Evolving technology, methodology and statistical approaches should help disentangle the relationships between these chemicals and health effects. However, with most of the statistically significant hormone alternations that have been attributed to environmental and occupational exposures, the actual degree of hormone alteration has been considered subclinical. Hence, more information is required on the biological mechanisms that may be affected by plastic additives and in particular, low-dose chronic exposures. Meanwhile we should consider strategies to reduce the use of these chemicals in plastic manufacture and/or develop and test alternatives (for example citrates are being developed as substitute plasticizers). This is the goal of the new field of green chemistry, which is based on the premise that development of chemicals for use in commerce should involve an interaction between biologists and chemists. Had this approach been in place 50 years ago it would probably have prevented the development of chemicals that are recognized as likely endocrine disruptors (Anastas & Beach 2007). There is also a need for industry and independent scientists to work more closely with, rather than against, each other in order to focus effectively on the best ways forward. For example, contrast comments on BPA by Bird (2005) with those of vom Saal (2005), and contrast comments in this volume on the safety of plastic additives by Andrady & Neal (2009) with those by Koch & Calafat (2009), Meeker *et al.* (2009), Oehlmann *et al.* (2009) and Talsness *et al.* (2009).

6. PRODUCTION, USAGE, DISPOSAL AND WASTE MANAGEMENT SOLUTIONS

Accumulation of plastic debris in the environment and the associated consequences are largely avoidable. Considerable immediate reductions in the quantity of waste entering natural environments, as opposed to landfill, could be achieved by better waste disposal and material handling. Littering is a behavioural issue and some have suggested that it has increased in parallel with our use of disposable products and packaging. Perhaps increasing the capacity to recycle will help to reverse this trend such that we start to regard end-of-life materials as valuable feedstocks for new production rather than waste. To achieve this will require better education, engagement, enforcement and recycling capacity (figure 1*a*–*f*). Unfortunately, we were unable to source a contribution on education and public engagement, but it is evident that social research on littering behaviour could be very informative. A recent report by EnCams in the UK examined attitudes towards littering in 2001 and then again in 2006. This indicated that despite greater awareness among the general public about the problems of littering, the propensity to litter had actually increased; five key attitudes and behaviours were noted and these offer valuable insight for future research (EnCams 2006). There is evidence that appropriate education can influence behaviour. For example, pre-production plastic pellets (a feedstock for production of plastic products, also described as nurdles or mermaids tears) account for around 10 per cent, by number, of the plastic debris recorded on shorelines in Hawaii (McDermid & McMullen 2004) and substantial quantities have been recorded on shorelines in New Zealand (Gregory 1978). These pellets have entered the environment through spillage during transportation, handling and as cargo lost from ships. In the USA guidelines (Operation Clean-Sweep, figure 1*e*) on handling of resin pellets are reported to have reduced spillage during trials (Moore *et al.* 2005). Conservation organizations such as the UK Marine Conservation Society play an important role in education, and the annual beach cleans they organize can be a good way to raise public awareness and to collect data on trends in the abundance of debris on shorelines (see www.mcsuk.org and Ocean Conservancy, International Coastal Cleanup www.oceanconservancy.org). However, there is a pressing need for education to reduce littering at source (figure 1*d* and *e*). This is especially important in urban settings where increased consumption of on-the-go/fast food coupled, in some locations, with a reduction in the availability of bins as a consequence of concerns about terrorism is likely to result in increased littering. Where plastic debris enters watercourses as a consequence of dumping or littering a range of strategies including catch basin inserts, booms and separators can be used to facilitate removal (figure 1*f*).

Substantial quantities of end-of-life plastics are disposed of to landfill. Waste generation statistics vary among countries and according to the rationale for data collection. For instance, plastics are a small component of waste by weight but a large component by volume. Temporal and spatial comparisons can thus be confounded, and data on quantities of waste recycled can be skewed according to categorization of various wastes. However, in many locations space in landfill is running out (e.g. Defra *et al.* 2006). It has also been suggested that because of the longevity of plastics, disposal to landfill may simply be storing problems for the future (Barnes *et al.* 2009; Hopewell *et al.* 2009). For example, plasticizers and other additive chemicals have been shown to leach from landfills (Teuten *et al.* (2009) and references therein). The extent of this varies according to conditions, particularly pH and organic content. There is evidence, however, that landfills can present a significant source of contaminants, such as BPA, to aquatic environments. Efficient treatment approaches are available and are in use in some countries (Teuten *et al.* 2009).

From a waste management perspective, the three R's—*reduce, reuse* and *recycle* are widely advocated to reduce the quantities of plastic and especially plastics packaging the waste we generate (figure 1*a*–*c*). Hopewell *et al.* (2009) outline the benefits and limitations of these strategies. They show that to be effective we need to consider the three R's in combination with each other and together with a fourth 'R', *energy recovery.* Indeed we also need to consider a 5th 'R', molecular redesign, as an emerging and potentially very important strategy. Hence, the three R's become five: 'reduce, reuse, recycle, recover and redesign'. There are opportunities to 'reduce' usage of raw material by down gauging (figure 1*a*) and there are also some opportunities to 'reuse' plastics, for example, in the transport of goods on an industrial (pallets, crates; figure 1*b*) and a domestic (carrier bags) scale. However, there is limited potential for wide-scale reuse of retail packaging because of the substantial back-haul distances and logistics involved in returning empty cartons to suppliers. Some of the energy content of plastics can be 'recovered' by incineration, and through approaches such as co-fuelling of kilns, reasonable energy efficiency can be achieved. These approaches have benefits compared with disposal to landfill since some of the energy content of plastics is recovered. However, energy recovery does not reduce the demand for raw material used in plastic production, hence it is considered less energy efficient than product recovery via recycling (WRAP 2006; Defra 2007). In addition, concerns about emissions from incinerators (Katami *et al.* 2002) can reduce the appeal of this waste disposal option. There is now strong evidence to indicate significant potential lies in increasing our ability to effectively recycle end-of-life plastic products (WRAP 2006, 2008; Defra 2007; fig 1*c*). Although thermoplastics have been recycled since the 1970s, the proportion of material recycled has increased substantially in recent

Figure 1. Solutions include: (*a*) measures to reduce the production of new plastics from oil, here an example showing how small changes in product packing reduced the weight of packaging required by 70%, while (*b*) re-useable plastic packing crates have reduced the packaging consumption of the same retailer by an estimated 30,000 tonnes per annum; and (*c*) recycling; here, bales of used plastic bottles have been sorted prior to recycling into new items, such as plastic packaging or textiles. Measures to reduce the quantity of plastic debris in the natural environment include: (*d*) educational signage to reduce contamination via storm drains and (*e*) via industrial spillage, together with (*f*) booms to intercept and facilitate the removal of riverine debris. (Photographs (*a*) and (*b*), and associated usage statistics, courtesy of Marks and Spencer PLC; (*c*) courtesy of P. Davidson, WRAP; (*d*,*e*,*f*) courtesy of C. Moore, Algalita Marine Research Foundation.)

years and represents one of the most dynamic areas of the plastic industry today (WRAP 2006, 2008).

The recycling message is simple; both industry and society need to regard end-of-life items, including plastics, as raw materials rather than waste. At present our consumption of fossil fuels for plastic production is linear, from oil to waste via plastics. It is essential to take a more cyclical approach to material usage, but achieving this goal is complex (Hopewell *et al.* 2009). Greatest energy efficiency is achieved where recycling diverts the need for use of fossil fuels as raw materials (figure 1*c*); good examples being the recycling of old polyethylene terephthalate (PET) bottles into new ones (closed-loop recycling) or where low-density polyethylene bottles are converted into waste bins (semi-closed loop). In addition to benefits as a consequence of more sustainable material usage, a recent life cycle analysis calculated that use of 100 per cent recycled PET rather than virgin PET to produce plastic bottles could give a 27 per cent reduction on CO_2 emissions (WRAP 2008; Hopewell *et al.* 2009).

There are some very encouraging trends, with growth in mechanical recycling increasing at 7 per cent per annum in western Europe. However, there is considerable regional variation in recycling rates and globally only a small proportion of plastic waste is recycled (see Barnes *et al.* (2009) for US data; see Hopewell *et al.* (2009) for European data). Items made of a single polymer are easier and more efficient to recycle than composite items, films and mixed wastes. As a consequence, it is currently not possible to recycle a substantial proportion of the packaging in a typical shopping basket (Hopewell *et al.* 2009). On reading the account by Hopewell *et al.* (2009), the ingenuity of the separation procedures for recycling is evident (Fourier-transform near-infrared spectroscopy, optical colour separation, X-ray detection), but one cannot help but wonder why similar ingenuity has not been focused on designing products for better end-of-life recyclability. Historically, the main considerations for the design of plastic packaging have been getting goods safely to market and product marketing. There is an increasing urgency to also design products, especially packaging, in order to achieve material reduction and greater end-of-life recyclability. Public support for recycling is high in some countries (57% in the UK and 80% in Australia; Hopewell *et al.* 2009), and consumers are keen to recycle, but the small size and the diversity of different symbols to describe a product's potential recyclability, together with uncertainties as to whether a product will actually be recycled if it is offered for collection, can hinder engagement. In our opinion, what is needed is a simplification and streamlining of everyday packaging, to facilitate recyclability, together with clearer labelling to inform users. One option could be a traffic light system so that consumers can easily distinguish from printed product labelling between packages that use recycled content and have high end-of-life recyclability (marked with a green spot), those that have low end-of-life recyclability and are predominantly made of virgin polymer (red spot), and those which lie between these extremes (amber spot). With combined actions including waste reduction, design for end-of-life, better labelling for consumers, increased options for on-the-go disposal to recycling and improved recycling capability, Hopewell *et al.* (2009) consider it could be possible to divert the majority of plastic from landfill over the next few decades (figure 1*a–c*). This will require consistency of policy measures and facilities among regions and will also require the cooperation of industry since ultimately there needs to be an acceptance of reduced usage and hence reduced income associated with the production of plastics from virgin polymer.

Molecular *redesign* of plastics (the 5th R) has become an emerging issue in green chemistry (Anastas & Warner 1998; Anastas *et al.* 2000; Anastas & Crabtree 2009) that should be incorporated within the design and life cycle analysis of plastics. In this context, green chemists aspire to design chemical products that are fully effective, yet have little or no toxicity or endocrine-disrupting activity; that break down into innocuous substances if released into the environment after use; and/or that are based upon renewable feedstocks, such as agricultural wastes. One of the fundamental factors limiting progress on all other R's is that the design criteria used to develop new monomers have rarely included specifications to enhance reusability, recyclability or recovery of plastic once it has been used. Typically, such assessments have only been made after a product entered the marketplace and problems involving waste and/or adverse health effects have begun to appear. Had the guiding principles of Green Chemistry (Anastas & Warner 1998) been available to inform the syntheses of polymers over the past century, perhaps some of the environmental and health concerns described in this Theme Issue would be more manageable. To date, the application of these design criteria to polymers has remained largely in the laboratory. Polylactic acid (PLA) (Drumright *et al.* 2000), a biodegradable polymer sourced from corn and potatoes, has entered the marketplace and has the potential to make a valuable contribution among other strategies for waste management. However, life cycle analyses are required to help establish the most appropriate usage, disposal (e.g. Song *et al.* 2009 illustrate relatively slow degradability of PLA in home composting) and hence labelling, of biopolymers such as this (WRAP 2009).

7. BIOPOLYMERS, DEGRADABLE AND BIODEGRADABLE POLYMER SOLUTIONS

Degradable polymers have been advocated as an alternative to conventional oil-based plastics and their production has increased considerably in recent decades. Materials with functionality comparable to conventional plastics can now be produced on an industrial scale; they are more expensive than conventional polymers and account for less than 1 per cent of plastics production (Song *et al.* 2009). Biopolymers differ from conventional polymers in that their feedstock is from renewable biomass rather than being oil-based. They may be natural polymers (e.g. cellulose), or synthetic polymers made from biomass monomers (e.g. PLA) or synthetic polymers made from synthetic monomers derived from biomass (e.g. polythene derived from bioethanol) (WRAP 2009). They are often described as renewable polymers since the original biomass, for example corn grown in agriculture, can be reproduced. The net carbon dioxide emission may be less than that with conventional polymers, but it is not zero since farming and pesticide production have carbon dioxide outputs (WRAP 2009). In addition, as a consequence of our rapidly increasing human population, it seems unlikely that there will be sufficient land to grow crops for food, let alone for substantial quantities of packaging in which to wrap it. One solution is to recycle waste food into biopolymers; this has merit, but will ultimately be limited by the amount of waste food available.

Biopolymers that are designed to breakdown in an industrial composter are described as 'biodegradables' while those that are intended to degrade in a domestic composter are known as 'compostable'. There are benefits of these biodegradable materials in specific applications, for example, with packaging of highly perishable goods where, regrettably, it can be necessary to dispose of perished unopened and unused product together with its wrapper. Song *et al.* (2009) show experimentally that degradation of biodegradable, as opposed to compostable, polymers can be very slow in home composters (typically less than 5% loss of biomass in 90 days). Degradation of these polymers in landfills is also likely to be slow and may create unwanted methane emissions. Hence, the benefits of biopolymers are only realized if they are disposed of to an appropriate waste management system that uses their biodegradable features. Typically, this is achieved via industrial composting at 50°C for around 12 weeks to produce compost as a useful product.

Some biopolymers, such as PLA, are biodegradable, but others such as polythene derived from bioethanol are not. A further complication is that degradable, as opposed to biodegradable, polymers (also called 'oxo-biodegradable', 'oxy-degradable' or 'UV-degradable') can also be made from oil-based sources but as a consequence are not biopolymers. These degradable materials are typically polyethylene together with additives to accelerate the degradation. They are used in a range of applications and are designed to break down under UV exposure and/or dry heat and mechanical stress, leaving small particles of plastic. They do not degrade effectively in landfills and little is known about the timescale, extent or consequences of their degradation in natural environments (Barnes *et al.* 2009; Teuten *et al.* 2009). Degradable polymers could also compromise the quality of recycled plastics if they enter the recycling stream. As a consequence, use of degradable polymers is not advocated for primary retail packaging (WRAP 2009).

There is a popular misconception that degradable and biodegradable polymers offer solutions to the problems of plastic debris and the associated environmental hazards that result from littering. However, most of these materials are unlikely to degrade quickly in natural habitats, and there is concern that degradable, oil-based polymers could merely disintegrate into small pieces that are not in themselves any more degradable than conventional plastic (Barnes *et al.* 2009). So while biodegradable polymers offer some waste management solutions, there are limitations and considerable misunderstanding among the general

Table 1. Synthesis of current knowledge, uncertainty and recommended actions relevant to environmental and human health concerns arising from current production, use and disposal of plastics.

	established knowledge	concerns and uncertainty	recommendations for industry, research and policy
production and use	plastics are inexpensive, lightweight, versatile, water resistant and durable annual growth in plastic production is approximately 9% (currently >260 Mt yr^{-1}) around 8% of world oil production is used to make plastics plastics bring extensive societal, human health and environmental benefits >33% of production is used for disposable items of packaging	is our usage of hydrocarbons for plastics sustainable? to what extent could biopolymers replace oil-based plastics? is there sufficient arable land for production of biomass (crops) required for biopolymers? to what extent does use of plastic powders as cleaning abrasives, and scrubbers results in direct release of particles to environment?	increase/incentivize material reduction and reuse construct life cycle analysis of production, disposal/recycling of major polymers (including biopolymers, degradable and biodegradable polymers) and plastic products develop alternative monomers, polymers and additives using green chemistry approaches revise international standards for and introduce accurate/ informative labelling of recyclable, 'degradable', 'biodegradable' and compostable polymers
disposal: waste management	plastics are a substantial part of domestic and industrial wastes in landfill recycling of some polymers (e.g. PET) has increased considerably in recent years, but substantial quantities of plastic waste not compatible with recycling biodegradable polymers typically require industrial composting and will not readily degrade in landfill biodegradable plastics can compromise recycling	are current disposal strategies sustainable—lack of space in landfill? to what extent do chemicals leach from plastic in landfill? little is known about the degradability or environmental fate of additives used in biodegradable polymers	increase/incentivize product design towards use of recycled feedstock and increased end-of-life recyclability improve methods to collect and separate plastic waste for recycling investment in/incentivize recycling operations standardize labelling so consumers can identify products with high end-of-life recyclability (traffic light system) research and monitoring of leachates from landfills
disposal: littering and dumping	plastic debris is common in marine habitats worldwide, including poles and deep sea the abundance of plastic debris is increasing/stabilizing (not declining) plastic debris is fragmenting, with pieces <20 μm on shorelines and in water column	to what extent will breakdown of plastic debris increase the abundance of small fragments in the environment? rates of accumulation of debris on land, in freshwaters and in the deep sea are not certain do biodegradable or compostable plastics degrade in natural habitats?	education/incentives to promote the value of end-of-life plastics as a feedstock for recycling education and associated enforcement on the wasteful and adverse ecological effects of plastic spillage, dumping and littering develop standard protocols and monitoring to evaluate trends in the abundance of plastic debris across in natural habitats cleaning programmes in natural, urban and industrial locations research on breakdown of degradable and biodegradables
issues relating to wildlife	>260 species are known to ingest or become entangled in plastic debris ingestion is widespread in some populations (>95% of individuals) and can compromise feeding entanglement in plastic debris can lead to severe injury and death	does ingestion of, or entanglement in, plastic debris have effects at the population level or can such effects combine with other stressors to do so? to what extent do plastics transport/release chemicals to wildlife? what are the consequences of the accumulation of small plastic particles (e.g. abrasives from cleaning applications) in the environment?	research to establish the distribution, abundance and environmental consequences of micro- and nano-plastic fragments research to establish potential for plastics to transport chemicals to food chain research to establish population-level consequences of ingestion and entanglement education, monitoring and cleaning (see above)

(*Continued*)

Table 1. (*Continued*)

	established knowledge	concerns and uncertainty	recommendations for industry, research and policy
issues relating to human health	some plastics contain potentially harmful monomers and additive chemicals, including flame retardants and plasticizers adverse effects of additives evident in laboratory animals measurable levels of chemicals used as additives/monomers are present in the human population Canadian government declared BPA a toxic substance. USA National Toxicology Program expressed concern for adverse health effects	what are the effects of low-dose chronic exposure to chemicals or mixtures of chemicals used as plastic monomers or additives? dose–response curves may not be monotonic and so should not be extrapolated in risk assessment	conduct cumulative risk assessment/management of plastic additives and monomers biomonitoring of body burdens of additives/monomers effects on susceptible subpopulations (babies, children) and on those with high-exposure risks evaluate effects of exposure to mixtures of additives/monomers design/validate appropriate species/protocols to assess chronic low dose exposures to additives/monomers by humans

public about their application (WRAP 2007). To gain the maximum benefit from degradable, biodegradable and compostable materials, it is, therefore, essential to identify specific uses that offer clear advantages and to refine national and international standards (e.g. EN 13432, ASTM D6400-99) and associated product labelling to indicate appropriate usage and appropriate disposal.

8. POLICY MEASURES

Our intention when preparing this Theme Issue was to focus on the science surrounding all aspects pertinent to plastics, the environment and human health. There are some omissions from the volume, such as input from social scientists on how best to convey relevant information to influence littering behaviour, consumer choice and engagement with recycling. These omissions aside, to be of greatest value the science herein needs to be communicated beyond a purely scientific audience (see recommendations in table 1). This is in part the role of a Theme Issue such as this, and the final invited contribution to the volume examines the science–policy interface with particular reference to policy relating to plastics. Shaxson (2009) considers this interface from the perspectives of industry, the scientist and the policymaker. She emphasizes the need for policy relating to plastic to weigh societal and economic benefits against environmental and health concerns. This is a diverse subject area that will require a range of policies to focus at specific issues, including polymer safety, material reduction, reuse, recycling, biopolymers, biodegradable and compostable polymers, littering, dumping and industrial spillage. There are a range of appropriate measures (National Research Council 2008) including information and recommendations (e.g. WRAP 2009), regulations (such as the Canadian Government restrictions on BPA in baby bottles), taxes (such as land fill tax, which incentivizes the diversion of waste from landfill to recycling), standards (such as EN 13432 covering compostable plastics) and allocation of funds for research, innovation and capacity building. However, the diversity of issues leads to an equally complex policy environment. In the UK, for example, there is not one, but many relevant policy interfaces and numerous policies. These activities are shared among several government departments, driven by national pressures, international obligations and European directives. In such a complex environment, even robust and clearly delivered information from the scientific community does not always have the most appropriate effects on the policy process.

Shaxson presents evidence from case studies on policies relating to plastic litter in the marine environment and land-based plastic waste. She indicates that many plastic-related policy issues fall into what are defined as unstructured or badly structured problems—in essence, problems that lack consensus and clarity in the relevant policy question and in some cases lack clarity in the relevant knowledge base to inform any decision. Shaxson suggests such circumstances will require a reflexive approach to brokering knowledge between industry, scientists and policymakers, and that scientists will need to be prepared to make and facilitate value judgements on the basis of best evidence. From a UK perspective, she advocates using the science within this volume to help develop a 'Plastics Road Map', similar to the recently completed Milk and Dairy Road Map (Defra 2008) to structure policy around plastics, the environment and human health and suggests that this be facilitated by appropriate and broad debate among relevant parties.

9. PLASTICS AND THE FUTURE

Looking ahead, we do not appear to be approaching the end of the 'plastic age' described by Yarsley and Couzens in the 1940s, and there is much that plastics can contribute to society. Andrady & Neal (2009) consider that the speed of technological change is increasing exponentially such that life in 2030 will be unrecognizable compared with life today; plastics will play a significant role in this change. Plastic materials have the potential to bring scientific and medical advances, to alleviate suffering and help reduce mankind's environmental footprint on the planet (Andrady & Neal 2009). For instance, plastics are likely to play an increasing role in medical applications, including tissue and organ transplants; lightweight components, such as those in the new Boeing 787, will reduce fuel usage in transportation; components for generation of renewable energy and insulation will help reduce carbon emissions and smart plastic packaging will no doubt be able to monitor and indicate the quality of perishable goods.

In conclusion, plastics offer considerable benefits for the future, but it is evident that our current approaches to production, use and disposal are not sustainable and present concerns for wildlife and human health. We have considerable knowledge about many of the environmental hazards, and information on human health effects is growing, but many concerns and uncertainties remain. There are solutions, but these can only be achieved by combined actions (see summary table 1). There is a role for individuals, via appropriate use and disposal, particularly recycling; for industry by adopting green chemistry, material reduction and by designing products for reuse and/or end-of-life recyclability and for governments and policymakers by setting standards and targets, by defining appropriate product labelling to inform and incentivize change and by funding relevant academic research and technological developments. These measures must be considered within a framework of lifecycle analysis and this should incorporate all of the key stages in plastic production, including synthesis of the chemicals that are used in production, together with usage and disposal. Relevant examples of lifecycle analysis are provided by Thornton (2002) and WRAP (2006) and this topic is discussed, and advocated, in more detail in Shaxson (2009). In our opinion, these actions are overdue and are now required with urgent effect; there are diverse environmental hazards associated with the accumulation of plastic waste and there are growing concerns about effects on human health, yet plastic production continues to grow at approximately 9 per cent per annum (PlasticsEurope 2008). As a consequence, the quantity of plastics produced in the first 10 years of the current century will approach the total that was produced in the entire century that preceded.

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