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Pim de Voogt *Editor*

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Reviews of Environmental Contamination and Toxicology Volume 259

Editor
Pim de Voogt

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Foreword

International concern in scientific, industrial, and governmental communities over traces of xenobiotics in foods and in both abiotic and biotic environments has justified the present triumvirate of specialized publications in this field: comprehensive reviews, rapidly published research papers and progress reports, and archival documentations These three international publications are integrated and scheduled to provide the coherency essential for nonduplicative and current progress in a field as dynamic and complex as environmental contamination and toxicology. This series is reserved exclusively for the diversified literature on "toxic" chemicals in our food, our feeds, our homes, recreational and working surroundings, our domestic animals, our wildlife, and ourselves. Tremendous efforts worldwide have been mobilized to evaluate the nature, presence, magnitude, fate, and toxicology of the chemicals loosed upon the Earth. Among the sequelae of this broad new emphasis is an undeniable need for an articulated set of authoritative publications, where one can find the latest important world literature produced by these emerging areas of science together with documentation of pertinent ancillary legislation.

Research directors and legislative or administrative advisers do not have the time to scan the escalating number of technical publications that may contain articles important to current responsibility. Rather, these individuals need the background provided by detailed reviews and the assurance that the latest information is made available to them, all with minimal literature searching. Similarly, the scientist assigned or attracted to a new problem is required to glean all literature pertinent to the task, to publish new developments or important new experimental details quickly, to inform others of findings that might alter their own efforts, and eventually to publish all his/her supporting data and conclusions for archival purposes.

In the fields of environmental contamination and toxicology, the sum of these concerns and responsibilities is decisively addressed by the uniform, encompassing, and timely publication format of the Springer triumvirate:

Reviews of Environmental Contamination and Toxicology [Vol. 1 through 97 (1962–1986) as Residue Reviews] for detailed review articles concerned with any aspects of chemical contaminants, including pesticides, in the total environment with toxicological considerations and consequences.

Bulletin of Environmental Contamination and Toxicology (Vol. 1 in 1966) for rapid publication of short reports of significant advances and discoveries in the fields of air, soil, water, and food contamination and pollution as well as methodology and other disciplines concerned with the introduction, presence, and effects of toxicants in the total environment.

Archives of Environmental Contamination and Toxicology (Vol. 1 in 1973) for important complete articles emphasizing and describing original experimental or theoretical research work pertaining to the scientific aspects of chemical contaminants in the environment.

The individual editors of these three publications comprise the joint Coordinating Board of Editors with referral within the board of manuscripts submitted to one publication but deemed by major emphasis or length more suitable for one of the others.

Coordinating Board of Editors

Preface

The role of *Reviews* is to publish detailed scientific review articles on all aspects of environmental contamination and associated (eco)toxicological consequences. Such articles facilitate the often complex task of accessing and interpreting cogent scientific data within the confines of one or more closely related research fields.

In the 50+ years since *Reviews of Environmental Contamination and Toxicology* (formerly *Residue Reviews)* was first published, the number, scope, and complexity of environmental pollution incidents have grown unabated. During this entire period, the emphasis has been on publishing articles that address the presence and toxicity of environmental contaminants. New research is published each year on a myriad of environmental pollution issues facing people worldwide. This fact, and the routine discovery and reporting of emerging contaminants and new environmental contamination cases, creates an increasingly important function for *Reviews.* The staggering volume of scientific literature demands remedy by which data can be synthesized and made available to readers in an abridged form. *Reviews* addresses this need and provides detailed reviews worldwide to key scientists and science or policy administrators, whether employed by government, universities, nongovernmental organizations, or the private sector.

There is a panoply of environmental issues and concerns on which many scientists have focused their research in past years. The scope of this list is quite broad, encompassing environmental events globally that affect marine and terrestrial ecosystems; biotic and abiotic environments; impacts on plants, humans, and wildlife; and pollutants, both chemical and radioactive; as well as the ravages of environmental disease in virtually all environmental media (soil, water, air). New or enhanced safety and environmental concerns have emerged in the last decade to be added to incidents covered by the media, studied by scientists, and addressed by governmental and private institutions. Among these are events so striking that they are creating a paradigm shift. Two in particular are at the center of ever increasing media as well as scientific attention: bioterrorism and global warming. Unfortunately, these very worrisome issues are now superimposed on the already extensive list of ongoing environmental challenges.

The ultimate role of publishing scientific environmental research is to enhance understanding of the environment in ways that allow the public to be better informed or, in other words, to enable the public to have access to sufficient information. Because the public gets most of its information on science and technology from internet, TV news, and reports, the role for scientists as interpreters and brokers of scientific information to the public will grow rather than diminish. Environmentalism is an important global political force, resulting in the emergence of multinational consortia to control pollution and the evolution of the environmental ethic. Will the new politics of the twenty-first century involve a consortium of technologists and environmentalists, or a progressive confrontation? These matters are of genuine concern to governmental agencies and legislative bodies around the world.

For those who make the decisions about how our planet is managed, there is an ongoing need for continual surveillance and intelligent controls to avoid endangering the environment, public health, and wildlife. Ensuring safety-in-use of the many chemicals involved in our highly industrialized culture is a dynamic challenge, because the old, established materials are continually being displaced by newly developed molecules more acceptable to federal and state regulatory agencies, public health officials, and environmentalists. New legislation that will deal in an appropriate manner with this challenge is currently in the making or has been implemented recently, such as the REACH legislation in Europe. These regulations demand scientifically sound and documented dossiers on new chemicals.

Reviews publishes synoptic articles designed to treat the presence, fate, and, if possible, the safety of xenobiotics in any segment of the environment. These reviews can be either general or specific, but properly lie in the domains of analytical chemistry and its methodology, biochemistry, human and animal medicine, legislation, pharmacology, physiology, (eco)toxicology, and regulation. Certain affairs in food technology concerned specifically with pesticide and other food-additive problems may also be appropriate.

Because manuscripts are published in the order in which they are received in final form, it may seem that some important aspects have been neglected at times. However, these apparent omissions are recognized, and pertinent manuscripts are likely in preparation or planned. The field is so very large and the interests in it are so varied that the editor and the editorial board earnestly solicit authors and suggestions of underrepresented topics to make this international book series yet more useful and worthwhile.

Justification for the preparation of any review for this book series is that it deals with some aspect of the many real problems arising from the presence of anthropogenic chemicals in our surroundings. Thus, manuscripts may encompass case studies from any country. Additionally, chemical contamination in any manner of air, water, soil, or plant or animal life is within these objectives and their scope.

Manuscripts are often contributed by invitation. However, nominations for new topics or topics in areas that are rapidly advancing are welcome. Preliminary communication with the Editor-in-Chief is recommended before volunteered review manuscripts are submitted. *Reviews* is registered in WebofScience™. Inclusion in the Science Citation Index serves to encourage scientists in academia to contribute to the series. The impact factor in recent years has increased from 2.5 in 2009 to 7.0 in 2017. The Editor-in-Chief and the Editorial Board strive for a further increase of the journal impact factor by actively inviting authors to submit manuscripts.

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Pim de Voogt

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Microplastics in the Food Chain: Food Safety and Environmental Aspects

József Lehel and Sadhbh Murphy

Contents

Abstract Plastic has been an incredibly useful and indispensable material in all aspects of human life. Without it many advances in medicine, technology or industry would not have been possible. However, its easy accessibility and low cost have led to global misuse. Basically, the production of the plastics from different chemical agents is very easy but unfortunately difficult to reuse or recycle, and it is thrown away as litter, incinerated or disposed of in landfill. Plastic once in the environment begins to degrade to very small sizes. Thus, many animals mistake them for food, so

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plastic enters a marine, terrestrial or freshwater food web. These microplastics although chemically inert have been shown to act as tiny "bio-sponges" for harmful chemicals found in the environment changing the nature of a plastic particle from chemically harmless to potentially toxic. It was believed that microparticles would simply pass through the gastrointestinal tract of animals and humans with no biological effect. However, studies have shown that they are sometimes taken up and distributed throughout the circulatory and lymphatic system and may be stored in the fatty tissues of different organisms. The result of the uptake of them showed potential carcinogenic effects, liver dysfunction and endocrine disruption. This review focuses on micro- and nanoplastics and their way entering marine and freshwater food webs, with particular attention to microplastic trophic transfer, their toxic side effects and influence to the human consumer in health and safety in the future.

Keywords Anthropogenic activity · Aquatic food chain · Environmental safety · Food safety · Freshwater fish · Marine fish

Abbreviations

ABS	Acrylonitrile butadiene styrene
BPA	Bisphenol A
FTIR	Fourier Transform Infrared Spectroscopy
GI	Gastrointestinal
HBDC	Hexabromocyclododecane
HDPE	High-density polyethylene
IPA	Isophthalic acid
LDPE	Low density polyethylene
NP	Nonylphenols
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PDBE	Polybrominated diphenyl ether
PE	Polyethylene
POP	Persistent organic pollutant
PP	Polypropylene
PPA	Polyphthalamide
PVC	Polyvinylchloride
SPI	Society of Plastic Industry
SUP	Single-use plastic
TPA	Terephthalic acid
UN	United Nations

1 Introduction

Plastic is intrinsic to modern life. Since the invention of Bakelite in 1930 plastic has lived up to its reputation as the "Material of a thousand uses" (Gilbert 2017). Human beings use plastic in different ways every single day, and it has propelled invention and advances in many industries including medicine, construction and engineering. The problem with plastics began with the development of a "throwaway culture" which has been feasible by the invention of "single-use plastics", most frequently used in the packaging of various products. This problem in countries that have underdeveloped waste disposal methods, to cope with the large volumes of plastic, has led to build-up of plastic materials in landfills, waste incinerators, or in the environment in the form of litter (Hayden et al. 2013; Shah et al. 2008). Plastic is favoured for its outstanding durability, but it is this trait which has led to problems associated with its degradation, especially when it reaches the environment.

It has been estimated that the amount of plastic entering the ocean yearly is eight million tonnes (Jambeck et al. 2015) and that plastic pieces floating around in the oceans water column could exceed 5 trillion (Eriksen et al. 2014). Plastic is accumulating in ecosystems at ever increasing rates. These plastic pieces have been found all around the world from deep ocean gyres to surface waters as well as in every terrestrial and freshwater habitat (Carbery et al. 2018; Rillig 2012).

Plastics are mostly made from petrochemical waste products of the fossil fuel industry, which are materials of high molecular mass usually derived from ethylene, propylene and styrene. During their manufacture and degradation greenhouse gases can be emitted such as ethylene, carbon dioxide and methane (Hayden et al. 2013; Soares et al. 2008). Various chemical additives can be added to the plastic during its manufacture depending on its potential/intended use. The top two additives used in plastic manufacture that were found in environmental plastic debris were (1) Phthalates such as Bisphenol A; (2) Flame retardants such as Nonylphenols (NP), Polybrominated diphenyl ethers (PDBEs) and hexabromocyclododecane (HBCD). The reason phthalates are added to plastic is that they increase the flexibility and durability (Oehlmann et al. 2009). The flame retardants are used in plastics as safety devices where the intention is to reduce the flammability of a product. These plastic additives may leach to the environment (Talsness et al. 2009). Plastic litter produced may become bioavailable to the organisms that reside there (Cheng et al. 2013). This is also how they become incorporated into marine, aquatic, or terrestrial food webs. Nonylphenols are mostly found in the effluent from wastewater treatment plants and have been found associated with many microplastics found as plastic debris (Mackintosh et al. 2004). These chemical additives have been linked to various health risks including endocrine disrupting activities, liver and kidney toxicity and teratogenicity. They can also leach into the environment in a similar way and are known as persistent organic pollutants (POPs). HBCD is often used in polystyrene products and has also been found in buoys used in fisheries and in marine debris, and has allegedly been linked to endocrine disruption and are also POPs (Al-Odaini et al. 2015; Yogui and Sericano 2009).

It is for this reason that it is important to produce, recycle, reuse and dispose of plastics in a way that is not wasteful or harmful to the environment to prevent unnecessary expenditure of chemical additives. In Germany there are waste processes in place that work very well whereas Ireland relies on shipping up to 95% of their plastic waste to other countries to be recycled, incinerated, or buried in landfill (O'Sullivan 2017; Patel et al. 2000).

Until 2017 China a significant amount of other countries' plastic and paper waste, but in December of that year, they declared that they would no longer be the world's dumping ground. So, countries have been faced with their own waste to deal with (O'Sullivan 2017).

The EU strategy on a circular economy in plastics includes a strong emphasis on improving the waste management of plastics, however, it is a complex process focusing to reducing waste, waste collection, sorting plastic types and improving recycling methods (European Commission 2018a). Certainly, the problems of wastes are intensified in that countries where there is no effective waste management system, and these countries can receive large amounts of plastic waste materials from the developed countries.

Most of the mismanaged plastic waste, and of the world's ocean plastics pollution has its origin in Asia. China produced the largest amount of plastic with about 60 million tonnes (MT) followed by the USA (38 MT), Germany (14.5 MT) and Brazil (12 MT) in 2018. Furthermore, highest quantity of the mismanaged plastic waste is also originated from China (28% of the global total waste) followed by Indonesia (10%), Philippines and Vietnam (6%), Thailand (3.2%), Egypt (3%), Nigeria (2.7%) and South Africa (2%). The amount of the mismanaged waste which can induce risks of ocean pollution is generally significantly lower in many countries of Europe and North America due to the modified and thus effective waste management, despite producing large quantities of plastic (Ritchie 2018).

Certainly, very large differences can be seen in the effectiveness of waste management across the world. In high-income countries (e.g. most of Europe, North America, Australia, New Zealand, Japan and South Korea), the waste management instillations and the infrastructure are very effective, because the discarded plastic wastes are stored in secure, closed landfills even if they are not recycled or incinerated. In many low-to-middle-income countries, the amounts of inadequately disposed waste can be high, thus there is a risk of pollution of rivers and oceans such as in many countries of South Asia and sub-Saharan Africa, where about 80–90% of plastic waste is stored and disposed inadequately (Ritchie 2018).

In Europe, the declaration for a ban on single-use plastic and the creation of a circular economy in 2019 were great steps forward on the road to tackling plastic waste production and disposal issues (European Commission 2019).

Plastic waste comes in many sizes such as macro-, meso-, microplastic, microfibres and nanoplastics. All sizes and types of plastic and their associated chemicals are making their way into the environment through legal and illegal dumping, littering and landfill. Macro- and mesoplastic cause obvious devastation to wildlife and nature through such processes as entanglement, as well as being an

Table 1 Type of microplastics (Batel et al. 2016)

Type of microplastics
Primary microplastic
It is often added to cosmetic products as exfoliant and then wash down the drain and into the freshwater rivers, lakes and the sea
Secondary microplastic
It is the result of larger meso- or macroplastics that have been broken down or degraded to smaller fragments by weathering through UV light and exposure to other physical or biological processes
Tertiary microplastic
They are plastic pellets that are the building blocks of plastic material

eye sore when found discarded or washed up in nature (Carbery et al. 2018; Hayden et al. 2013; Lusher et al. 2017).

Microplastics are divided into primary, secondary and tertiary materials (Batel et al. 2016) (Table 1).

If these tiny plastics make their way into ecosystems, they are often mistaken for a food source by a selection of invertebrates (within marine, freshwater and terrestrial ecosystems), as well as juvenile fish species and enter the food chain or causing damage to these creatures after direct and indirect ingestion (Rillig 2012).

Although chemically inert, plastic has shown to have the property of a "bio-sponge". This means that it is very conducive to the adherence of various chemicals both added to the plastic during production or taken up from the environment in which it has found itself in such as a polluted part of the ocean, freshwater rivers, lakes or the soil (Rochman et al. 2013b). This quality makes plastic potentially toxic if ingested due to the nature of the chemicals which have been found adsorbed to the surface of microplastics (Batel et al. 2016; Raza 2018).

Based on the simulation performed by Koelmans et al. (2017) most of the plastic (99.8%) entered the ocean is settled below the ocean surface layer with an annual additional 9.4 million tonnes settling. Due to the different types of plastics and the wide variety of chemical substances absorbed or adsorbed to them, their toxic effects and mechanisms of action are variable, and manifold resulted in widely differing responses in individuals and species with different biological characteristics (Koelmans et al. 2017).

Furthermore, the microplastics in the aquatic ecosystem can be taken up by the animals during the food web. The marine zooplankton can ingest relatively small amount of microplastics settled in the ocean surface layer (<0.07%), however, it can be enriched and concentrated in the food chain including mesopelagic fish, seabirds and other aquatic animals. Thus, large amount of microplastics can be removed by marine organisms via ingestion of plastic debris, however, they are again returned to the ocean surface layer after gut passage and egestion settled in faecal pellets. Due to it, the plastic debris can be sedimented to the ocean floor resulted in impacts to mesopelagic and benthic communities (Koelmans et al. 2017).

Microplastics have been aptly described as being ubiquitous in the environment; meaning that they have been found everywhere. This fact raises concerns regarding potential microplastic incorporation into the human food chain. It has been proven through various studies that humans ingest plastic from an array of sources (Van Cauwenberghe et al. 2015). It is important to determine the main routes of ingestion and how they can be quantified and prevented, and to conduct toxicological studies to determine the concentrations in which they cause harm or are toxic to human consumers. Many studies have been done with these questions in mind. Most have been conducted under laboratory conditions and exposures have often been much higher than would be found naturally in the environment, however, they still provide an indication as to the problems microplastics may cause if they continue to build up in the environment or within organisms.

There have been already developed many projects on methods for quantifying plastic in the environment, although there is need for more standardization. So, it is difficult to grasp the scale of the problem that is why it is necessary to develop new methods for detecting plastics within food items and study bioindicator species to help us monitoring the plastics in the ecosystem and their effects. We must look at the trophic cascade to determine potential hazards that could be inflicted upon humans and animals within the complex food webs of various ecosystems (Batel et al. 2016; Carbery et al. 2018).

The problem is that plastic is not the only potential risk issue facing our environment. Climate change, over population, political unrest, habitat fragmentation and loss, forest fires, loss of biodiversity, collapse of fish stocks due to overfishing, invasive species, acidification of the oceans, and pollutants from other sources such as heavy metals also play their part in threatening global biodiversity and species worldwide, but plastic, too, contributes to the pressures facing in the natural world. The plastic problem is just additive to these pressing concerns and it is important to grasp the impact it may have in terms of food safety for human and animal consumers and on protecting the biodiversity of our wildlife habitats. It must be noted that whatever is damaging to the environment will be damaging to humans in some way.

"In isolation, microplastics might not be the single most toxic (lethal or sublethal) environmental contaminant. However, there are consistent past, present, and future trends of increasing a near-permanent plastic contamination of natural environments at a global scale" (Geyer et al. 2017).

This literature review is based on the most recent studies available about the trends in plastic production and human interaction with plastic, the routes in which plastic may enter the food chain and the potential toxic or harmful effects they may pose to invertebrate and vertebrate organisms as well as food safety and security issues regarding humans as the main consumer of interest.

2 Plastic Material

The word plastic was derived from the Greek word "Plastikos" which means "capable of being shaped or moulded". This aptly describes the ductile and malleable nature of the material we know as plastic. It is a material consisting of a wide range of synthetic or semi-synthetic organic compounds which can be moulded into solid objects (Lusher et al. 2017).

"Plastic" is an umbrella term that refers to a very large family consisting of many different materials all with varying characteristics, properties and uses. Plastic can be utilized in many areas of life and this explains the ubiquitous nature of the product. Plastic polymers have innumerable applications from microplastics, food packaging, clothing, toys, medical implants, piping, plumbing, furniture, etc. (Lusher et al. 2017). The invention of plastic initially meant less reliance on natural materials such as wood, bone, tortoiseshell, horn, metal, glass and ceramics, which was a benefit to the environment. However, due to humans ever increasing reliance on plastic and its ability to find its way into the environment, among others plastic has proven quite the burden on the natural world, accumulating in terrestrial, marine and aquatic ecosystems (Andrady 2011; Machado de Souza et al. 2018).

Plastic is usually derived from either fossil fuel based or bio-based materials. Most plastics are not or only limited degradable, however, one part of them can be degradable if disposed of correctly, but plastic disposal most often follows three main routes: landfill, incineration, recycling, or littering (Hayden et al. 2013; Machado de Souza et al. 2018; Shah et al. 2008). From the aspect of environmental pollution plastic has become a focus since the fact that much of it finds its way into the environment through many routes. It was estimated that annual eight million tonnes of plastic waste enter the ocean then these plastics interact with almost 700 marine species (Andrady 2011; Gall and Thompson 2015). However, plastics can be incinerated without significant waste production (except for carbon dioxide production) in appropriate establishments. Basically, a well-designed incineration process can remove more polycyclic aromatic hydrocarbons, polychlorinated biphenyls and dioxins from the incoming air used in the installation than is emitted by the waste stream.

Plastic can be categorized according to size: macroplastics, mesoplastics, microplastics and nanoplastics, but there is a wide range of their sizes recommended by different articles. Plastics less than 5 mm in size or between 5 and 1,000 μm are regarded as microplastics (Smith et al. 2018; Van Cauwenberghe and Janssen 2014). Nanoplastics have not been settled a standard size definition, but generally they are below 0.1 μm (Boyle and Örmeci 2020; Lambert and Wagner 2016). Macro- (>25 mm) and mesoplastics (5–25 mm) typically make up the plastic litter that is visible to the naked eye; while microplastics and nanoplastics consisting of plastic we usually cannot see easily or at all (Smith et al. 2018). Macroplastics can cause problems such as entanglements, ingestion in larger animals, are an eyesore in the environment, etc., but micro- and nanoplastics can cause problems such as bioaccumulation and biomagnification within the food chain. If ingested, these plastics also pose a threat due to their potentially toxic effects when acting as a bio-sponge (Lusher et al. 2017).

It has been documented and will be discussed later how microplastics interact with or are ingested by many small invertebrates such as Daphnia, Mussels and Earthworm across a range of ecosystems with organisms being affected either at the tissue or cellular level (Farrell and Nelson 2013; Lwanga et al. 2017; Setälä et al. 2014).

Sometimes plastic can have additives incorporated into their creation process for them to have a variety of uses. These additives have the potential to be harmful to the environment and cause also harm to body tissues in large quantities (Andrady 2011). These include: Ultraviolet stabilizers; Lubricants; Colourants; Flame retardants; Plasticizers; Anti-oxidants; Phthalates; BPA; Nonylphenol (Lusher et al. 2017; Tsuguchika et al. 2011; Yogui and Sericano 2009). Microplastics also play a role in transferring persistent organic pollutants adsorbed to their surfaces. In several studies microplastics were shown to have rather high amounts of harmful substances such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, dichlorodiphenyl-trichloro-ethanes, perfluoro-octane-sulfonate and perfluoro-octane-sulphonamide (Lusher et al. 2017). These substances are found as pollutants in the environment while also being attracted to and adsorbed by microplastics that are found in the same environment as the pollutant. The consequences of ingesting these particles have been studied in small invertebrates and fish and their detrimental effects have been noted under laboratory conditions. However, in a natural setting the ingestion of these chemical-laden microplastics may not have the same affect at least to people, who are exposed to relatively few of these (Bakir et al. 2014; Lusher et al. 2017). Microplastics also exist as microfibres from polyester and nylon clothing which, once washed, release tiny fibres which are washed down the drain and reach the same fate and consequence as microplastics (Vianello et al. 2018).

2.1 Top 5 Plastics Found in Waste

Global generation of most important types of the primary plastic wastes was as follows in 2015: 57 million tonnes (MT) for low-density polyethylene, 55 MT for polypropylene, 42 MT for polyphthalamide and 40 MT for high-density polypropylene followed by polyethylene terephthalate (32 MT), polystyrene (17 MT), polyurethanes (16 MT) and polyvinyl chloride (15 MT) (Geyer et al. 2017).

2.1.1 Low Density Polyethylene (LDPE)

LDPE has a Society of Plastic Industry (SPI) resin ID code 4. LDPE was developed in 1939 by an accidental leak of trace oxygen during an experiment to reproduce polyethylene. It is produced by the ICI process for producing ethylene and is a thermoplastic (Gilbert 2017). LDPE has a density range of 0.917–0.930 g/cm^3. It is a flexible but tough plastic that can undergo temperatures of up to 80°C (Lusher et al. 2017). When compared to High-Density Polyethylene it has roughly 2% more branching on its carbon atoms that have weaker intermolecular forces. This in turn translates to higher resilience but a lower tensile strength, it also has a lower density due to its molecules being less tightly packed and has also fewer crystalline molecules due to the side branches. It produces methane and ethylene when exposed to solar radiation. This material is used for an array of products such as containers, six pack rings, juice and milk cartons, computer hardware and hard discs, playground slides, plastic hinges on shampoo or ketchup bottles, plastic wraps and corrosion resistant work surfaces (Tripathi 2002).

2.1.2 Polypropylene (PP)

PP has an SPI resin ID code 5 meaning it is recyclable. Polypropylene is also a thermoplastic polymer with many applications. It is produced from the monomer propylene using chain growth polymerization. PP is very similar to polyethylene with a density between 0.895 and 0.92 g/cm^3. It is a tough and flexible material especially when copolymerized with ethylene. It can be used as an engineering plastic. When it was discovered, it was produced in large amounts, competing with materials such as acrylonitrile butadiene styrene (ABS). It is a very economical plastic with good fatigue resistance, it has excellent resilience against many forms of stress such as impact and freezing, and it is also resistant to corrosion and chemical leaching. Polypropylene has many uses. It is most famous for its plastic living hinges; however, it can also be used in clothing, stationery, packaging, carpets, clear bags and piping. In areas where other plastics may melt propylene will not. Many medical devices are made from PP (Gilbert 2017; Malpass 2010).

2.1.3 Polyphthalamide (PPA)

Polyphthalamide (PPA) belongs to the polyamide (nylon) family and it is in fact a subset of thermoplastic synthetic resins characterized by 55% more moles of carboxylic acid portion of repeating units in the polymer chain comprised of a combination of terephthalic (TPA) isophthalic (IPA) acids. The backbone of this polymer made from aromatic acids means that this material has a very high melting point, chemical resistance and stiffness. This means that PPAs have a better chemical resistance, higher strength and stiffness even at higher temperature, they resist creep and fatigue, have good resistance to warping and have also good dimensional stability while not being sensitive to moisture absorption (Malpass 2010).

2.1.4 High-Density Polyethylene (HDPE)

HDPE stands for high-density polyethylene. It is an often-recycled plastic with an ISO resin code of 2. HDPE is a thermoplastic polymer produced from the monomer ethylene. It is mostly used for plastic bottles, packaging and piping as it has a high strength to density ratio.

The density of HDPE can range from 930 to 970 kg/m^3. HDPE has a slightly higher density than LDPE but has much less branches which means it has stronger intermolecular forces and tensile strength than LDPE. It is a harder plastic and less transparent and can also undergo higher temperatures (120°C) for short periods of time. However, it cannot withstand an autoclave.

It has a wide range of applications some of which are: water pipes, wood plastic, plastic surgery skeletal and facial reconstruction, shampoo bottles, sewage mains, etc. (Nagar 2006).

2.1.5 Polyethylene (PE)

PE has an ISO resin code of 1. There are several kinds of polyethylene as described above. It is a thermoplastic although it can become thermoset if modified. PE has a low strength, hardness and rigidity but can be modelled into many shapes. It has a low melting point around 105°C, but melting temperatures can vary. It is very chemically stable and is not affected by strong acid or base or minor oxidizing agents. It is not readily degraded but some bacteria have been known to degrade this plastic, it can also become brittle when exposed to UV light. It is a very good insulator, and it has massive application opportunities in packaging, drink bottles, 3D printing, thin solar cells and cellotape (Nagar 2006).

ISO resin codes can help the consumer figure out whether a plastic is recyclable or not. However, there is considerable consumer confusion when it comes to what they indicate and also many plastic products are made of more than one plastic type meaning they are more difficult to recycle (Gilbert 2017).

3 Degradation of Plastic Polymers

Degradation of plastic is defined as reducing the molecular weight of the polymers within the plastic material (Andrady 2011). Plastic is well known for its durable and stable nature and these characteristics make the degradation process in the environment incredibly slow. This is way why plastics persist in nature when not disposed of correctly. Plastic polymers which make their way into the environment are exposed to many different types of weathering influences. There are five main methods by which plastic degrades, the name of the process refers to the cause and type of degradation. (Andrady 2011; Bellas et al. 2016; Gewart et al. 2015) (Table 2).

Due to their larger surface to volume ratio microplastics usually degrade faster than larger meso- or macroplastics. This is because their polymer surface is exposed and prone to breakdown by chemicals or enzymes. The result of degradation at the surface is for the inside to become exposed for degradation and results in the plastic becoming brittle and disintegrating into smaller particles or flakes (Hayden et al. 2013).

Most often this process begins with photodegradation due to exposure to UV light from the sun, which gives the initial energy required to incorporate oxygen into the polymers. Plastic polymers begin to degrade in an aerobic environment that will

Table 2 Main degradation methods (Andrady 2011; Bellas et al. 2016; Gewart et al. 2015)

Main degradation methods
1. Hydrolytic degradation – reacting with water
2. Exposure to heat or thermooxidative degradation – a slow process involving oxidative breakdown in a moderate temperature range
3. Thermal degradation – degradation involving high temperatures which are not normally present in the environment naturally
4. Photodegradation through UV light exposure
5. Biodegradation within microbial cells by cellular enzymes

inevitably lead to thermodegradation. Over time, the plastic polymers become more and more brittle and break into smaller particles as the polymer chain decreases in molecular weight. This process will then lead to biodegradation by microorganisms. These microbes convert the polymer chains into biomolecules or carbon dioxide. This process takes very long, up to 50 or more years to fully degrade, however, there is dispute as to whether these polymers ever fully degrade as some scientists believe they can persist in the environment or landfill sites infinitely. Low temperatures and oxygen availability such as conditions in the ocean or in river ways can greatly lengthen the degradation time of any plastic material (Andrady 2011; Hayden et al. 2013). This is why plastic can persist for long periods of time in landfill and in the ocean as there is less oxygen, and it is exposed to cold temperatures (Andrady 2011).

3.1 Biodegradable Plastic

The invention of "bio-plastic" has arisen alongside the increasing need for alternative materials to plastic with a shorter and more efficient degradation time. Three main types have emerged thus far, these include

- oxo-biodegradable plastic which contains polyolefin plastic, and this contains metal salts in small amounts that aid the degradation process.
- biodegradable plastic that can be broken down into water and carbon dioxide by microorganisms
- bio-based plastics which are made from biological and renewable sources, within them is a weaker polymer structure which leads more readily to degradation when compared to the plastics currently in use.

Many of these plastics are now available and labelled often as "compostable", however, they must first reach compost and little research has been done on their degradation time and effect on the environment (Lusher et al. 2017).

4 Plastic Waste Disposal

4.1 Burying in Landfill

Landfill is defined as the burying of waste on excavated land. This has got obvious negative connotations as it is using land that could otherwise be used in a more profitable way such as for forestry or agriculture. Burying plastic in landfill leads to very slow degradation as the environment lacks oxygen and plastic degrades better in an aerobic environment. This slow degradation means that the land is therefore not viable for many years (Andrady 2011; Hayden et al. 2013).

There is another problem with burying plastic in landfill in which some plastics can leach pollutants as they degrade (Zhang et al. 2004). These pollutants include and are not limited to volatile organic chemicals such as xylene, benzene, toluene, ethyl/trimethyl benzenes and bisphenol A (BPA), a compound used widely in many plastics and resins (Lusher et al. 2017; Urase et al. 2008; Xu et al. 2011). These compounds are a cause for concern if they are continuously being exposed to the environment through the dumping of large amounts of plastic in landfill, however, it is BPA that has been under the most scrutiny in recent years.

BPA has been linked to numerous health risks and some research has shown that BPA can leach into food, beverages and the soil from containers that are made with BPA. Exposure to BPA has become a special concern because of possible side effects on the brain and prostate gland of foetuses, infants and children, even being linked to adverse behaviour in children. BPA has also been listed as an endocrine disruptor (Lusher et al. 2017). Moreover, when it comes to landfill BPA can leach into the surrounding soil and it has been correlated to increased populations of sulphate reducing bacteria in soil which has led to a rise in production of hydrogen sulphide, this can have lethal consequences in high concentrations (Hayden et al. 2013; Tsuchida et al. 2011).

4.2 Incineration

Incineration is the burning of waste products. Many countries use this method to some degree. Two positive aspects when comparing to landfill are that there is much less space being used up in this process and in some cases the heat generated from burning the materials may be used for energy. On the other hand, many pollutants are released to the atmosphere through the process of burning (Zhang et al. 2004). These include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), toxic carbon and oxygen based free radicals, smoke (particulate matter), PCFDs and particulate bound heavy metals. Greenhouse gases, ethylene, methane and CO_2 are also released in this process. In some cases, the negative effects of the combustion emissions can be controlled by various means; (1) activated carbon addition, (2) flue gas cooling, (3) acid neutralization and (4) ammonia, addition to the combustion chamber and/or (5) filtration (Yassin et al. 2005).

Due to landfill and incineration having many negative environmental effects recycling was developed as a potential alternative (Astrup et al. 2009).

4.3 Recycling

Plastic waste is being produced globally at an even growing scale per year and this increases the pressure on landfill and incineration as disposal methods for the material. This magnifies the environmental drawbacks outlined above with both the space and time needed for landfill and the harmful pollutants produced by each method. Recycling is therefore being investigated as the most sustainable solution for the repurposing of the plastic produced each year. Unfortunately, at present only approximately 9% of single-use plastics are recycled annually. Not all plastic can be recycled to the same degree and so they must first be separated (Hayden et al. 2013; Tartakowski 2010).

Plastic materials have various melting points, so mixing the polymers of different plastics can affect the characteristics of the plastic. For example, if HDPE and PP are melted together, they will form a brittle and weak secondary plastic product (Sanchez-Soto et al. 2008). The key to successful recycling methods is the accurate separating of mixed plastics and the grouping of identical materials. There are various ways of separating plastics including; Tribo electric separation, X-ray fluorescence, Fourier transformed infrared technique, Froth flotation method, Magnetic density separation and Hyper spectral imaging technology (Kumar et al. 2015). Recycling can be divided into four main techniques, such as primary, secondary, tertiary and quaternary (Table 3). Each has pros and cons to its techniques, however, once recycled will forgo some of its properties with relation to tensile strength, dimensional accuracy and wear properties. Recycling can be divided into mechanical and chemical recycling. The first three types of recycling unfortunately do have their limitations because plastic materials can only undergo 2–3 recycling cycles before they become an unviable material, in which phase the last type of recycling is utilized (Kumar et al. 2015; Sadat-Shojai and Bakhshandeh 2011; Subramanian 2000).

5 EU Legislation Regarding Plastic Waste

In Europe alone 25 million tonnes of plastic waste is generated every year with less than 30% being collected for recycling. The ten most commonly found single-use plastic items together make up 86% of all single-use plastics and therefore roughly 43% of all marine litter found on European beaches by the latest count. This, together with discarded fishing gear, which accounts for 27% of plastic, together