Ecotoxicity of Microplastic Pollutants to Marine Organisms: a Systematic Review

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Ecotoxicity of microplastic pollutants to marine organisms: A Systematic Review

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Abstract Plastic is a ubiquitous material used across the globe. It is easily transported to various habitats and can then be ingested by animals, with the potential to bioaccumulate up the food chain further. Although classified as solid waste, some plastics can be considered hazardous waste due to the chemicals used in the production process and those that can be adsorbed, such as hydrophobic pollutants in seawater. Plastics can break down into secondary particulate plastics, or be microscopically primary plastics, smaller than 5mm. Marine organisms of all sizes can mistake plastic for food or consume prey with microplastics. This can cause detrimental toxic effects at a cellular, biochemical, and muscular level. This research uses a systematic quantitative literature review (SQLR) method to determine the most common polymers, hazardous chemicals, and marine organisms to ingest microplastic and incur ecotoxicological consequences. The results indicated polyethylene (PE), polypropylene (PP), and polystyrene (PS) to be the topmost common polymers, with sizes between 1-100 µm. Plastic was observed to be a sink for non-additive pollutants more than a vector. Persistent organic pollutants (POPs) were the most common pollutants found. Biological impacts and side effects included mortality, reproductive effects, genotoxicity, accumulation, and behavioral effects. Further research is needed regarding the interrelationship of plastic polymers, additives, and non-additives combined for inducing toxic effects.

Keywords: Microplastics, Bioavailability, Marine Pollution, Toxicity, Marine organisms

1 Introduction

In 2016, the global production of plastic surpassed the 320 million tons mark, with approximately 5-13 million tons of this production ending up in the world's oceans per annum (Silva et al., 2018). Plastics are typically categorized by size. Secondary plastics are those larger than 5mm such as plastic bags, caps, and plastic rings which can directly enter oceans through polluted rivers or illegal dumping (Silva et al., 2017; Bradney et al., 2019; Xu et al., 2020). Primary plastics are smaller than 5mm and typically derive from micro beads found in cosmetics, bathroom products such as soap and body washes, and laundry detergents (Gallo et al., 2018; Alimba & Faggio, 2019). These enter marine ecosystems in large quantities through indirect pathways such as wastewater systems (Li et al., 2019; Bradney et al., 2019).

Neither primary nor secondary plastics naturally biodegrade, which means they persist indefinitely within the environment without completely disappearing (Gallo et al., 2018). Instead, plastics simply break down over time into smaller microplastic particles, which are now common features of marine environments (Silva et al., 2017; Xu et al., 2020). Marine organisms from every trophic level now tolerate consumption of plastic whether through direct ingestion, or trophic transfer by indirectly absorbing microplastics (Rochman et al., 2013; Hardesty & Wilcox, 2011; Peda et al., 2016; Samir Ali et al, 2021). Research of microplastics has thus far primarily focused on direct effects in fish, and larger marine animals from ingestion of secondary plastics. Evidence of histopathological damage in fish tissues has been found as a result of plastic pollution (Samir Ali et al., 2021).

While microplastics themselves are problematic for marine organisms, the chemicals associated with them are equally problematic. Plastic production uses polymers containing chemical additives some of which are known endocrine disruptors, such as Bisphenol A (BPA) (Hermabessiere et al., 2017). These chemicals may be harmful even in low concentrations to marine biota (Peda et al., 2016) as they leach from degrading plastics via abiotic or biotic processes. Microplastics can provide a pathway for transference of detrimental chemicals to marine organisms, potentially causing large-scale biological toxicity (WOR, 2010; Thompson et al., 2009; Rochman et al., 2013; Ziajahromi, Neale & Leusch, 2016). This pathway is known as the "vector effect" (Peda et al., 2016).

The release of highly toxic compounds deteriorates water quality. Plastic may act as carrier for organic pollutants, chemicals, and heavy metals quantifying the ecotoxic potential. Depending on the hydrophobic nature, and ratio of surface area to volume, of plastic types they can enhance aggregation with other pollutants (Samir Ali et al., 2021). Even though current research identifies the vector effect as a key threat to marine organisms, the pathway remains a contested topic requiring examination for more effective environmental management (Varotsos & Krapivin, 2019).

The focus on the toxicological effects of primary and secondary plastic borne chemicals is still developing (Gallo et al., 2018; Thompson et al., 2009; Rochman et al., 2013; Eriksen et al., 2014; UNEP, 2018). However, we know more than ever about the environmental impacts of chemical pollutants. Currently between 1 and 3% of chemicals used worldwide are environmentally detrimental (WOR 2010). These include heavy metals such as lead and mercury, organic contaminants and persistent organic pollutants (POPs) (REF). "A discussion at the eleventh meeting of the Open-ended Working Group of the Basel Convention recognizes that plastic wastes may contain potentially hazardous substances, including additives such as plasticizers and flame retardants, or may be contaminated by hazardous substances, and as such may pose a risk to human health and the environment, including marine ecosystems" (Marine Litter Topic Group, 2019).

The problems with chemical pollution, plastic waste and how they become microplastics are multifaceted. The issues introduced in this paper are highly relevant today when unfortunately, marine pollution is abundant. The effects and impacts are important to explore in order for researchers to help decision makers better understand the severity, and how they can establish possible solutions from drawn conclusions. Using existing literature this review aims to examine microplastics and associated pollutants in the marine environment. Their potential ecotoxicological and biological effects are analyzed through addressing the following;

1. Chemicals most easily absorbed by microplastics in marine environments,
2. Identified marine species negatively impacted by transferred microplastics and associated chemicals,
3. The trophic effects of marine species exposure to microplastic pollutants.

This paper uses a systematic quantitative literature review (SQLR) to examine the topics. Additionally, discussing established and recommended international solutions combating plastic pollution. The interaction of microplastics and associated chemicals are explored to understand how they may be biologically transferrable to marine organisms. Sources of plastic in the ocean and the overall management of plastics are discussed briefly to understand transportation pathways to the environment. Waste classification is demonstrated to determine any hazardous potential. The ecotoxic potential from waste for marine organisms is further evaluated from the results. Finally, any limitations, gaps, and future research considerations of this topic are concluded.

1.1 Overview of the dynamics of plastics and pollutants

Plastic breaks down into particulate plastics, otherwise known as micro (<5 mm) and nano (<100 nm) plastics, over time. Photodegradation and other weathering processes are environmental conditions that cause plastic to break down into secondary particulate plastic (Wang et al., 2020; Landrigan et al., 2020). Typical plastic items found inside a household include bags, bottles, lids, food packaging, and textile fibers from washing machines. Plastics from fishing gear, agriculture, and industrial pellets are amongst the industrial types that form part of the collective marine debris alongside household items (Gallo et al., 2018).

Plastics are a mixture of polymer and monomer chemicals (Gallo et al., 2018; Worm et al., 2017). The most common, representing 90% of the global production is, "low and high-density polyethylene (LDPE, PE, HDPE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET)" (Ivar do Sul & Costa, 2014). Certain plastics (e.g., PVC, PS, polyurethane, and polycarbonate) have the ability to adsorb other chemicals and pollutants and then potentially increase in toxicity as a vector (Rochman et al., 2013; Bradney et al., 2019; Worm et al., 2017; Seltenrich, 2015). The exemplified plastics can be hazardous due to the monomers or additives within them; otherwise, most plastic polymers are low in toxicity due to their insolubility in water and biochemical inactiveness (Worm et al., 2017). Additives can include coloring agents, flame-retardants, antimicrobials, fillers, plasticizers, and other material changing elements (Worm et al., 2017).

Bradney et al. (2019) explained the 'vector-effect' as, contaminants' behavior being altered by adsorbing to microplastics. The three vector stages are environmental, organismal, and cellular. Firstly, contaminants are transported to a new environment. Then, organismal is when a contaminant adsorbed by plastic is ingested. Finally, the plastic, if small enough, can travel into cells, resulting in bioavailability and bioaccumulation (Seltenrich, 2015; Bradney et al., 2019). Bradney et al. (2019) define bioavailability as "a compound's ability to either adsorb onto or to cross an organism's biological membrane."

Adsorption depends on multiple factors, including; the type and surface area of the plastic, functionalization of surfaces where natural organic matter attaches, environmental conditions (e.g., pH, salinity, temperature), surface charge, and trace element oxidation status (Bradney et al., 2019; Sorensen et al., 2020). Microplastics interact predominantly with contaminants such as inorganic pollutants (e.g., trace elements) and persistent organic pollutants (POPs) (Bradney et al., Rochman et al., 2013; Gallo et al., 2018; Tang et al., 2020). Seltenrich (2015) acknowledged the hydrophobic nature of POPs as being why they preferentially sorb to plastics in the ocean. Therefore, plastics act as a sink for these pollutants and have been demonstrated to contain high magnitudes of pollutants compared to the water collected from (Thompson et al., 2009; Worm et al., 2017; Seltenrich, 2015).

The pollution level of the water where plastics reside influences the concentration of chemicals in marine debris. Tracing back to the derivation of pollution, this is dependent on transport pathways and the concentration of chemicals in the manufacturing process. While plastics initially act as a sink for pollutants such as POPs, they can release those contaminants when transported to cleaner waters. This overview highlights the complexity of ecotoxicity potential and why there may be controversy over definitive outcomes (Thevenon, Carroll, & Sousa, 2014; Ivar do Sul & Costa, 2014).

A classic example of an additive widely discussed and recognized by society is Bisphenol A (BPA). This can be used to produce polycarbonate (PC) plastic water bottles, food containers, used in the medical industry, and for epoxy plastic paint for protecting ship hulls from corrosion. BPA is of concern because it has estrogen hormone mimicking potential. BPA also is not chemically bound thus can leach into a surrounding environment upon the breakdown of the associated plastic. Experiments have shown salinity in seawater can cause an acceleration of the leaching process of BPA. BPA is not the only additive that has this capability. Phthalates are an example added to PVC products (Worm et al., 2017; Thevenon, Carroll, & Sousa, 2014).

1.2 Sources of pollutants and microplastics

Whether microplastics are either primary or secondary, depends on their origin. Industrial resin pellets, plastic in personal care products (e.g., hygiene and cosmetic), scrubs and abrasives from cleaning agents, washing synthetic clothes, insect repellants and sunscreen, and synthetic clothing drilling fluids are amongst many examples of primary microplastics (Alimba and Faggio, 2019; Bradney et al., 2019; Thevenon, Carroll, & Sousa, 2014; Seltenrich, 2015; Xu et al., 2020). Secondary plastics come from larger plastic items that break down into smaller fragments through biological, chemical, and physical processes (Bradney et al., 2019; Alimba and Faggio, 2019; Seltenrich, 2015). They can also derive from chipped paint and fibers from fishing rope and aquaculture nets (Bradney et al., 2019).

According to Landrigan et al. (2020), “Ocean pollution is a complex mixture of plastic waste, toxic metals, manufactured chemicals, oil spills, urban and industrial wastes, pesticides, fertilizers, pharmaceutical chemicals, agricultural runoff, and sewage. More than 80% arises from land-based sources”. Other land-based points of entry for plastics and pollutants include wastewater treatment plants (WWTPs), landfills, outfalls for wastewater, urban and stormwater runoff, tourism, poor waste disposal and management, and illegal dumping (Thevenon, Carroll, & Sousa, 2014; Alimba and Faggio, 2019; Bradney et al., 2019). Aquatic sources are aquaculture, nautical, and fishing activities (Thevenon, Carroll, & Sousa, 2014). Seltenrich (2015) also identified nurdles, plastic pellets used to produce plastic items, as both land and ocean-based source spilling from ships and water treatment facilities.

Bradney et al. (2019) discussed plastic mulch and biosolids used in industry as having the potential to contain high quantities of microplastics. The extent to which a large concentration will be transported into rivers and eventually the ocean depends on erosion and runoff. However, one of the most discussed sources of microplastics is WWTPs.

Most microplastics are contained in sewage sludge in the treatment process. The concentration reduces towards the end of the treatment stages to such where <3% of microplastics can be found in the effluent (Li et al., 2019). Li et al. (2019) and Bradney et al. (2019) mention that even if the percentage is small, millions to trillions of microbeads may still be released into aquatic environments. The sludge can also be applied as fertilizer, which means any microplastics that were initially removed during the treatment stages can leach into soils through runoff (Gallo et al., 2018).

Raju et al. (2018) discussed Australia's case for microplastics released from outfalls with treated wastewater. They said in Sydney, a typical primary treatment facility can release up to 460 million particles in a day into the marine habitat. The volume of effluent discharged also determines the amount released (Raju et al., 2018). Li et al. (2019) raised an issue regarding the harmfulness of microplastics discharged from WWTPs. The changes in physicochemical properties of microplastics during treatment stages may increase the adsorption potential of metal pollutants. This is due to mechanical abrasion and microbial functions during treatment (Li et al., 2019).

1.3 Importance and concerns

1.3.1 Possible issues for marine organisms

Marine organisms within all trophic levels (i.e., the food chain) can mistake plastic waste for food (Seltenrich, 2015). Evidence suggests waste is mistaken for potential prey and selected based on shape, color, and smell. A classic example publicized is a turtle mistaking a plastic bag for jellyfish. Birds either ingest plastic from foraging or mistaking a particular item for an animal similar to the turtle, such as Albatrosses with red plastic as squid (Thevenon, Carroll, & Sousa, 2014; Alimba & Faggio, 2019). Bradney et al. (2019) confirm with this notion of feeding habits that the size, color, density, and abundance of plastic are critical for initial bioavailability. Generally, more toxicological consequences occur with smaller sized plastic including micro and nano particles (Alimba & Faggio, 2019; Tang et al., 2020).

Laboratory and field-based control experiments have provided insight into understanding the possible impacts of microplastics on observed vertebrates and invertebrates. Biomarkers, within selected organisms used as bio-indicators, which are biochemical, molecular, and histopathological (i.e., tissue and disease), have been studied to better understand physiological and metabolic impacts in marine organisms (Alimba & Faggio, 2019; Tang et al., 2020; Landrigan et al. 2020).

Seltenrich (2015) discusses the research of an Ecotoxicologist, Heather Leslie, concerned with the particle toxicity of micro-plastics alone. Heather concluded that "microplastics even without adsorbed contaminants could induce immunotoxicity responses including altered gene expression, and cause cell death." This means organisms can contend with harmful effects from microplastic generally along with other chemical stressors (Seltenrich, 2015; Tang et al., 2020; Wang et al., 2020). Bradney et al. (2019) also discuss cell death, or cytotoxic damage, with fish suggesting ingested metals are the cause. Alimba and Faggio (2019) addressed other consequences of ingested plastics and suggested they can block proper food intake leading to digestion issues, increased morbidity, and mortality.

In a comprehensive review by Luís Carlos de Sá et al. (2018), they identified fish, molluscs, small crustaceans, and large crustaceans to be the most commonly analyzed marine organisms for the effects of microplastics. Luís Carlos de Sá et al. (2018) suggest there is a lack of analysis on vertebrates other than fish that are likely to play important roles in food webs. However, the groups mostly studied are still of large concern due to their positions in the food chain and the potential to bioaccumulate microplastics and pollutants (Luís Carlos de Sá et al., 2018).

1.3.2 Possible issues for the food chain

Plastic, depending on the type, usually takes tens to hundreds of years to decompose. During this time as it breaks into smaller pieces this influences uptake by marine organisms throughout the food chain (Gallo et al., 2018). Alimba & Faggio (2019) suggests microplastics may be more toxicological the smaller they are, thus appears to have potential to increase risks for marine organisms.

Worm et al. (2017) and Seltenrich (2015) similarly pointed out there is accumulative evidence for trophic transfer, and potential for bioaccumulation, of plastic and associated chemical pollutants through the food web as organisms assume the residual chemical burden of their prey. This can occur in many ways, for example, when benthic filter feeders, such as mussels or baleen whales, consume prey-containing microplastics (i.e., trophic transfer) according to Gallo et al. (2018) and Worm et al. (2017). Benthic filter feeders such as mussels have been shown to then transfer microplastics in this way to benthic predators (Worm et al., 2017).

Another example from Worm et al. (2017) is the observation of microplastics in the gastrointestinal tract of pinnipeds (e.g., sea lions and walruses) and cetaceans demonstrate trophic transfer from fish to top predators. Gallo et al. (2018) warned of current scientific evidence suggesting endocrine disruptor activity from chemicals associated with microplastics, which are ingested through feeding mechanisms of some filter feeders like mussels and baleen whales.

Seltenrich (2015) discussed laboratory experiments concerning zooplankton and larger predators ingesting microplastics mistaken for food. The experiments demonstrated that chemical additives, adsorbed pollutants, and metals in microplastics could leach into marine organisms' tissues and guts. Seltenrich (2015) controversially states this process has not been proven to occur naturally. Gallo et al. (2018) mentioned microplastics have physically influenced various zooplankton species' mortality due to chronic levels of exposure and despite any other reactions internally occurring.

1.4 Management of pollutants and plastics

The scientific evidence that currently exists and concerns regarding this issue has been enough to encourage action by all sectors of society (Gallo et al., 2018; Landrigan et al., 2020). However, the effort required is ongoing and will need everyone's engagement from the individual to government, plastic producers, scientists, and industry (Worm et al., 2017; The World Bank produced a list of the top 20 countries found to mismanage plastic waste. Some African and Asian countries listed are producing little known effort towards reducing or recycling plastic waste (Alimba & Faggio, 2019). Landrigan et al., 2020). Xanthos and Walker (2017) analysed international market-based strategies and mentioned policies began in 2014 for the management of plastic microbeads. Whilst interventions for plastics bags had started as early as 1991.

The Department of Agriculture, Water and the Environment (2020) recognize the fundamental issues with microbeads and state they are not captured by most wastewater treatment systems, thus ending up in aquatic ecosystems. In 2016 in a Meeting of Environment Ministers, a voluntary phase-out of plastic microbeads was agreed to. By 2019 a National Waste Policy Action Plan was established and was intended for the business sector and governments to phase-out 100% of microbeads from targeted products. As of 2020 the Australian Government reported a successful phase-out (Department of Agriculture, Water and the Environment, 2020).

The use, sale, and manufacturing of microbeads are steadily becoming banned as demonstrated in one example. Microbead management measures are only newly adopted by a few countries according to Xanthos and Walker (2017). There are reportedly only a limited number of studies measuring the effectiveness of reduction strategies thus far (Prata et al., 2019; Xanthos and Walker, 2017). Education and increasing awareness are still important for policy creation, and minimizing plastic pollution. There is evidence of improvement in this area as demonstrated by citizens rejecting microbead products (Prata et al., 2019).

In general, however the threat of marine plastic pollution is evermore present. Some plans such as the *Threat Abatement Plan for the impacts of marine debris on vertebrate marine life* (TAP) created in 2009 and reviewed in 2014 under recognition of the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) were unsuccessful in their abatement strategies and have had to revise measures. The revised plan recognizes the level of threat microplastics in particular pose to ecosystems and marine species, according to the Commonwealth of Australia (2016).

Gallo et al. (2018) emphasized the importance of engaging organizations within the food and consumption sector to improve packaging and materials used, in order to reduce the availability of plastic waste and toxic chemicals. Gallo et al. (2019) called for more initiation in creating alternatives to POPs in plastics and other harmful contaminants in product design, through more decisive policy action based on evidence. Prata et al. (2019) agree on the matter of improving design or using alternative materials to reduce microplastic production and consumption. However, it is important for countries to firstly have an effective waste management system (Nielson et al., 2020). Table 1 comprises more management solutions already in place, developing, and proposed in the literature.

Table 1 Management solutions for plastic debris

	Management Solution	**Details of Solution**	**Reference**
International	Environmental Earth Day Network	Ending plastic pollution by Earth Day 2020, through significant clean up	Alimba & Faggio (2019)
	United Nations Clean Seas Campaign	Insists on government to implement plastic reduction policies, supports industry in terms of minimizing packaging and redesigning products, encourages people to change their consumer behaviour and waste habits	Worm et al. (2017)
	International Maritime Organization	Banned dumping waste at sea	Seltenrich (2015)
	United Nations (UN) Convention on the Law of the Sea	Legal framework for plastic pollution. “Articles 207-211	Thevenon, Carroll & Sousa (2014); Landrigan

	(UNCLOS)	refer to the prevention, reduction and control of pollution and here States are called on to adopt laws and regulations, and to prevent, reduce and control pollution of the marine environment from land-based sources, sea-bed sources, by dumping, and from maritime vessels”	et al. (2020)
Policy	Environmental Protection Agency (EPA)	Evaluating flame retardant additives from plastic, and then develop a protocol for manufacturers requiring the provision of data on chemical migration	Seltenrich (2015)
	Plastic Packaging	Curb unnecessary packaging demand, using something similar to deposit-refund schemes for plastic waste collection, banning micro beads in personal care products	Gallo et al. (2018)
Industry	Plastic Disclosure Project	“Improve accountability and implementation of reduced plastic use by private and public sectors”	Gallo et al. (2018)

Urban	Improved waste collection and management systems in developing countries	Reduce plastic input into marine environments	Gallo et al. (2018)
New	Global Convention on Plastic Pollution	Require producers to declare ingredients in plastic products for consumers, to help inform of their risk potential	Worm et al. (2017)
		Provide an avenue for new research into alternatives and management improvements	
	Legislation and regulation	Increase responsibility for managing plastic at the end of use including extending producer responsibility	Seltenrich (2015); Worm et al. (2017)
		Encourage the creation of a closed loop system for resource management with zero waste in landfill	
	Plastic generation of biodegradable design	Redesign plastics to ensure biodegradability, no way of collecting chemicals long-term, and using new innovative design principles	Seltenrich (2015)

2 Methodology

This paper identifies research papers related to marine pollution and ecotoxic effects on marine organisms using a systematic quantitative framework (a.k.a SQLR). According to Pickering & Byrne (2013), this method allows researchers to systematically search the literature using online database and other sources to find all relevant papers that fit specific criteria, entering information about each study into a personal database, then compiling tables that summarize the current status of the literature. The result is a structured quantitative summary of the field. The SQLR is useful as an initial step for further analysis, including identifying suitable data sets for meta-analysis.

The SQLR database was made with MSOffice software. Selection criteria included institutional reports and academic literature, which provided detailed pollutant results and their global impacts on any marine species. Sources that were selected for the SQLR database were peer-reviewed journal articles and discussion papers. Other papers were utilized in discussing evidence and supporting information. Online databases such as, Web of Science; Science Direct; Scopus; and ProQuest, were utilized for searches using the following keywords: *'marine' 'ocean' 'plastics' 'microplastics' 'sink' 'vector' 'pollution' 'pollutants' 'trace elements' 'adsorb' 'trace metals' 'chemicals' 'contaminant' 'ecology' 'ecotoxic' 'species' 'marine organisms' 'biomarker' 'biology'.* Keywords were used in combination or as search refining terms to improve results. The literature surveyed included published papers during the years of 2006-2019.

The literature was also categorized by 'Journal Discipline' with papers often falling under two to three disciplines of Environmental Science, Toxicology, Pharmacology, Environmental Chemistry, or Aquatic Ecology and Toxicity. Papers were then refined into categories for methods, experiment details, and data (e.g., quantitative and qualitative). The results of the literature were organized into subcategories for effects (e.g., positive or negative, discussed or tested, microplastic size dependency, lab reality or life reality etc.) and specific groups for pollutants, plastics, and polymers, and micro plastic sizes (<5µm).

Organisms identified also had sub categories for identifying taxonomy, preferred prey items, life stage, habitat (e.g. pelagic, benthic, etc.), and trophic level. The biological effects were organized into uptake factors, biomarkers, biological parameters (e.g., muscle, organs, etc.), and other identifiers (e.g., mortality, hormone levels, growth, reproduction, etc.). The aim was to include literature that encompassed all, or a large majority, of aspects including microplastics, polymer types, pollutants, biomarkers, and marine organisms' effects.

A total of 33 papers were sourced from the online databases. However, only 18 were most suitable for the aspects within the SQLR database. All figures in the results were produced using MSOffice, from the SQLR database. The objectives of this paper were to:

- Conduct a literature review on microplastic pollution and the adsorption of pollutants in marine environments
- Collect data to identify the specific types of plastics and pollutants that are commonly found to be associated with the issue of hazardous waste and plastic pollution in the ocean
- Research and understand the potentially harmful effects of microplastics and the pollutants adsorbed by microplastics
- Collect data to inform the research question of identifying the marine animals observed to ingest microplastics
- Summarise and analyse the data to then discuss the outcomes of the research and conclusions drawn

3 Results

3.1 Findings on plastics and polymers

The most common plastic polymers found out of all papers from the SQLR were PE (14), PP (7), PS (5), Polyvinyl chloride (PVC) (3), Polyethylene terephthalate (PET) (2), Polyvinyl alcohol (PVA) and Polyamide (PA) (1). This is consistent with industrial production output globally and in the literature about microplastics tested (Ivar do Sul & Costa, 2014; GESAMP, 2016; Burns & Boxall, 2018; Bradney et al., 2019). However, Luís Carlos de Sá et al. (2018) mentioned, "PP, polyester, and PA particles were underrepresented in laboratory studies considering their widespread detection in field-based studies."

While the most common size of microplastics found was 1-10 and 10-100 µm (29% of papers each), followed by 100-1000 and 1000-5000 µm (21% of papers each). Although plastic additives were not a significant component of this research, they must be understood and identified to conceptualize plastic waste impacts. Hermabessiere et al. (2017) identified the most common additives in marine ecosystems as "polybrominated diphenyl ethers (PBDE), phthalates, nonylphenols (NP), BPA, and antioxidants."

3.2 Bioavailability of microplastic pollutants

According to the SQLR data 10 papers reported plastic to be a sink of trace element contaminants, whilst only 6 of these papers indicated plastic to act as a vector also. The reasons for this are varied including the dynamic processes discussed, the organism in question, contamination levels, and the inherent hazardous effects of microplastics themselves through ingestion and additives. Also, correlation does not always equate to causation. Ziajahromi, Neale, and Leusch (2016) state PE and PP are examples of 'rubbery' polymers. They supposedly have greater sorption capacity for HOCs in comparison to PVC, which is a 'glassy' polymer.

Bayo et al. (2018) states, “the bioavailability of these pollutants, once they reach the target organism, depends on partitioning limitations from the microplastics and their ability to be metabolized by the organism." Bakir et al. (2016) point out increases in the internal concentration of pollutants occurs if the uptake via plastic is more significant than uptake via other routes. Similarly, for the other way around with decreases in internal concentrations, such as if microplastics adsorb pollutants in the gut.

Bakir et al. (2016), Hermabessiere et al. (2017), and Wang et al. (2018) disagree with hypotheses, that microplastics can act as a vector for chemical contaminants to organisms as modeling suggests this would be negligible naturally compared to other uptake routes. In saying that, Bakir et al. (2016) does include models that have not incorporated the possible role of factors meant to enhance desorption from microplastics including gut surfactants, pH, or temperature.

3.3 Marine pollutants identified

The results of this research showed POPs was the highest pollutant category identified, followed by trace metals and other organic contaminants, as the most common non-additive pollutants associated with plastic and marine pollution. For trace heavy metals Copper (Cu) and Zinc (Zn) were the two non-additives found the most amongst the literature, followed by Lead (Pb), Cadmium (Cd), Chromium (Cr), Manganese (Mn), and Nickel (Ni). Mercury (Hg) and Arsenic (As) were the lowest identified. ChemSec (2019) produced the SIN (Substitute It Now) list used in the hazard classification table from REACH's legislation from the European Commission. The list contains more than 900 substances of SVHC. ChemSec (2019) states these substances represent severe threats to our health and the environment. They also provide some suggestions for non-toxic alternatives. Any substances classified as CMR in the list are determined to be carcinogenic, mutagens, and reprotoxic. CMR chemicals damage DNA, are initiatives of cancer, and threaten the sexual function of unborn children. Many additives to polymers are classified as CMR by the EU or are generally toxic (ChemSec, 2019). Table 2 outlines the classifications for all suitable plastic additives and non-additive pollutants found in this study's literature.

Cu is listed under Annex IX and Annex I in the Basel Convention (2019). Zn is listed under Annex I and Annex IX in the Basel Convention (2019). They are wastes to be controlled but are not hazardous unless they contain Annex I material to an extent causing them to exhibit Annex III characteristics. Pb however, is classified as carcinogenic, mutagenic, or toxic to reproduction. Pb is restricted under Annex XVII by REACH (ChemSec, 2019). As mentioned, Bezerra, Lacerda & Lai (2019) found batoids to accumulate these trace metals, including Pb, listed in this paper. According to Ziajahromi, Neale, and Leusch (2016), microplastics and trace metals interactions are extensively reported in the literature, for MPs to act as a transport vector. However, more research is needed in this area as microplastics were identified as more of a sink than a vector for non-additives still.

Phenanthrene and Anthracene are both listed in REACH as substances of very high concern (SVHCs) (ChemSec, 2019). Frydkjaer, Iversen, and Roslev (2017), and Kleinteich et al. (2018) used phenanthrene and athracene in their studies for plankton and bacterial communities. These PAHs, combined with microplastics, induced less response than the pollutants alone in both cases. Anthracene is persistent, bio accumulative, and toxic, according to ChemSec (2019). Thus, although MPs were not a severe vector of these pollutants, their presence in the water column still poses a threat to marine organisms.

3.4 Ecotoxicity of identified marine organisms

Typically, the smaller the organism, the smaller the microplastic associated with uptake. For example, the results indicate plankton and molluscs ingested plastics within the ranges of 10-100 µm (Avio et al., 2015; Gallo et al., 2018; Frydkjaer, Iversen & Roslev, 2017). However, this is not always the case, as in the instance of benthic filter feeders and the common goby, which ingested PE spheres between 1-5 µm (Luís et al., 2015). The vast majority of papers (9) were also discussed or tested with primary plastic beads compared to fibers or fragments (4). This is interesting because Burns and Boxall (2018) and de Sá et al. (2018) determined fragments and fibers to be the predominant microplastic found in the marine environment compared to beads.While some academic papers do not conceive microplastics and adsorbed pollutants as a vector, six organisms were identified through the SQLR to experience impacts from contaminants (Table 3). Of those, only two discussed the harmful effects of microplastics alone being the cause. These were from Cole et al. (2015) and Lusher et al. (2015) for the Copepod and True's beaked whale. However, the effects are significant to note for understanding ecotoxicological impacts from MPs, and which polymers they were.

Worm et al. (2017) produced a comprehensive review on microplastics and suggest several possible pathways of microplastic pollution entrance to marine organisms. Worm et al. (2017) suggests they can enter through “ingestion or membrane uptake, and affect energy allocation, growth, and reproduction, likely influencing every level of organisation from subcellular to population”. Anbumani and Kakkar (2018) agree with these outcomes regarding toxic triggers from microplastics. At a cellular level the proposed outcomes of microplastic uptake across a membrane involve stress response, altered cellular division, elevated antioxidant responses, and altered fatty acid metabolism. Through ingestion, outcomes may include altered feeding, increased metabolic demand, and reallocation of energy reserves. Leading to reduced growth, decreased reproductive output, and therefore eventual population decline (Worm et al., 2017). Anbumani and Kakkar (2018) mentioned, the complexity of toxic responses in organisms occupying the top of the food chain becomes greater at the higher the level of biological organization.

Table 2. Hazards associated with plastic pollution (additives and non-additives). Adapted from ChemSec – SIN List to include relevant plastic additive, and non-additive pollutants found in the literature (ChemSec, 2019; European Chemicals Agency, 2019)

- CMR*: Carcinogenic, Mutagenic or toxic to Reproduction (ChemSec, 2019)
- NA**: Not in SIN list
- Annex XIV: List of substances subject to authorization
- Annex XVII: Restrictions on the manufacture, placing on the market and use of certain dangerous substances, mixtures, and articles
- Repr. 1A or 1B: Reproductive toxicity, adverse effects on sexual function and fertility
- Basel Convention – Annex IX: wastes not covered in Article 1, paragraph 1 (a), of this Convention unless they contain Annex I material to an extent causing them to exhibit an Annex III characteristic. (p. 74)
- Basel Convention – Annex VIII: hazardous wastes under Article 1, paragraph 1 (a) of this Convention, and their designation on this Annex does not preclude the use of Annex III to demonstrate that a waste is not hazardous (p. 66)

Additive (A) or Non-Additive (NA)	**Name**	**SIN Group**	**Reason for inclusion/on SIN List**	**Hazard class and category code(s)/Toxic effects**	**REACH status**	**SQLR Database Papers reported**	**Reference**
NA	Anthracene	Polyaromatics	Substance is concluded to be PBT by European Chemicals Bureau PBT Working Group	PBT (Persistent, bio accumulative, and toxic)	Candidate list	1	Kleinteich et al. (2018)

NA	Lead	Lead compounds	Classified CMR* according to Annex VI of Regulation 1272/2008	Repr. 1A; Acute Tox. 4; STOT RE 2; Aquatic Acute 1; Aquatic Chronic 1	Candidate list Restriction list (annex XVII)	3	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019); Kroon, Streten, & Harries (2017)
NA	Mercury	Mercury compounds	Classified CMR* according to Annex VI of Regulation 1272/2008	Repr. 1B; Acute Tox. 2; STOT RE 1; Aquatic Acute 1; Aquatic Chronic 1	Restriction list (annex XVII)	2	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019)
NA	Cadmium	Cadmium compounds	Classified CMR* according to Annex VI of Regulation 1272/2008	Pyr. Sol. 1; Carc. 1B; Muta. 2; Repr. 2; Acute Tox. 2; STOT RE 1; Aquatic Acute 1; Aquatic Chronic 1	Candidate list Restriction list (annex XVII)	3	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019); Kroon, Streten, & Harries (2017)
NA**	Arsenic	-	-	Annex I; Annex VIII (Basel Convention, 2019)	-	2	Bezerra, Lacerda, & Lai (2019); Kroon,

							Streten, & Harries (2017)
NA**	Copper	-	-	Annex IX; Annex I (Basel Convention, 2019)	-	4	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019); Kroon, Streten, & Harries (2017); Brennecke et al. (2016)
NA**	Zinc	-	-	Annex I, Annex IX (Basel Convention, 2019)	-	4	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019); Kroon, Streten, & Harries (2017); Brennecke et al. (2016)
NA**	Chromium	-	-	Annex IX (Basel	-	3	Bezerra, Lacerda, &

				Convention, 2019)			Lai (2019); Kroon, Streten, & Harries (2017); Luis et al. (2015)
NA**	Manganese	-	-	Annex IX (Basel Convention, 2019)	-	3	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019); Kroon, Streten, & Harries (2017)
NA**	Nickel	-	-	Annex IX (Basel Convention, 2019)	-	3	Bezerra, Lacerda, & Lai (2019); Bradney et al. (2019); Kroon, Streten, & Harries (2017)
NA**	DDT	-	-	Annex B to the Stockholm Convention with its		2	Bakir et al. (2016); Bezerra, Lacerda, &

				production and/or use restricted for disease vector control purposes in accordance with related World Health Organisation			Lai (2019); Stockholm Convention (2008a)
NA	Phenanthrene	Polyaromatics, Petroleum	Substance is concluded to be a vPvB SVHC by ECHA Member State Committee	-	Candidate List	1	Kleinteich et al. (2018)
NA**	Polycyclic Aromatic Hydrocarbons (PAHs) – Pyrene; General	-	-	Annex XV restriction proposals	-	5	Avio, et al. (2015); Kroon, Streten, & Harries (2017); Frydkjaer, Iverson, & Roslev (2017); Kleinteich et al. (2018); Gallo et al. (2018)
NA**	Polychlorinated	-	-	Annex A (Elimination –	-	2	Bayo et al. (2018);

	Biphenyls (PCBs) - General			Stockholm Convention). Parties to the Stockholm Convention can no longer produce PCBs and are obliged to stop using this chemical. Existing equipment may continue to be used until 2025.			Bezerra, Lacerda, & Lai (2019); Stockholm Convention (2008b)
A	Bisphenol A	Bisphenols	Toxic to reproduction; endocrine disrupting properties	Repr. 2; STOT SE 3; Eye Dam. 1; Skin Sens. 1	Candidate list CoRAP list Restriction list (annex XVII)	-	Hermabessiere et al. (2017)
A	Diisobutyl phthalate	Phthalates	Classified CMR* according to Annex VI of Regulation 1272/2008	Repr. 1B	Candidate list Authorisation list (annex XIV)	-	Hermabessiere et al. (2017)
A	Dibutyl phthalate, DBP	Phthalates	Classified CMR* according to Annex VI of Regulation 1272/2008	Repr. 1B; Aquatic Acute 1	Candidate list Authorisation list (annex XIV) Restriction list (annex XVII)	-	Hermabessiere et al. (2017)
A	Benzyl butyl phthalate, BBP	Phthalates	Classified CMR* according to Annex VI of Regulation	Repr. 1B; Aquatic Acute 1; Aquatic Chronic 1	Candidate list Authorisation list (annex XIV)	-	Hermabessiere et al. (2017)

			1272/2008		Restriction list (annex XVII)		
A	Dioctyl phthalate	Phthalates	Endocrine disruptor properties. In vivo reproductive and developmental effects in daphnia and fish.	No harmonized CLP classification	Restriction list (annex XVII)	-	Hermabessiere et al. (2017)
A	DEHP; Bis(2-ethylhexyl) phthalate	Phthalates	Classified CMR* according to Annex VI of Regulation 1272/2008	Repr. 1B	Candidate list Authorisation list (annex XIV) Restriction list (annex XVII)	1	Bakir et al. (2016); Hermabessiere et al. (2017)

Table 3. Observed ecotoxicity of microplastics and pollutants in marine organisms

Test system	Organisms	Details of microplastics, size/concentration	Details of Pollutants	Duration of exposure	End points	Observations	Biomarkers/ Bioindicators	Reference
Fish	European sea bass *Dicentrarchus labrax*	3 different treatment diets for control, native polyvinyl chloride	PAHs HCHs DDTs PCBs	90 days	Uptake Cellular	Moderate to severe related to exposure times	Histopathological alterations in Intestine	Peda et al. (2016)

	(PVC) and polluted polyvinyl chloride (PVC) pellets				Intestinal functions can be in some cases totally compromised. Evident in the distal intestine of fish fed with polluted PVC pellets	Leukocyte infiltrations and the increase in population of rodlet cells are typical responses to stress conditions	
Common goby *Pomatoschistus microps*	Polyethylene spheres 1–5 µm	Chromium (Cr)	96h	Uptake Cellular Mortality Predatory Performance	(5.6–28.4 mg/l) Cr (VI) was found to be toxic to P. microps early juveniles Cr and MP <67% decreased predatory performance, and <31% inhibition AChE activity Cr(VI) concentrations higher than 3.9 mg/l caused oxidative damage in L-est fish but not in	AChE LPO levels in L-est	Luís et al. (2015)

						M-est fish.		
Mollusk	Mussel *Mytilus galloprovincialis*	Polyethylene and polystyrene 100-1000 µm group and <100 µm group	PAHs (Pyrene) 0.5 mg/L (low, L), 5 mg/L (medium, M) and 50 mg/L (high, H)	3-7 days	Uptake	Bioaccumulation in tissues. Cellular effects alterations of immunological responses, lysosomal compartment, peroxisomal proliferation, antioxidant system, neurotoxic effects, onset of genotoxicity	Hemolymph, Digestive glands and gills, Cellular effects, DNA gene expression	Avio et al. (2015) Gallo et al. (2018)
Plankton	Cladoceran; Daphnia magna	Polyethylene – regular shaped beads (10–106 µm) and irregular fragments (10–75 µm) 0.7-50 particles per animal per day at exposure concentrations of	Phenanthrene	24h	Ingestion, Egestion	Acute effects Egestion of irregular fragments was slower than that of microplastic beads Polyethylene microplastic sorbed less phenanthrene compared to natural plankton	N/A	Frydkjaer, Iversen and Roslev (2017)

		0.0001–10 g/L				organisms		
Crustacean	Copepod *Calanus helgolandicus*	20 µ m polystyrene beads (75 microplastics mL−1)	N/A	24h	Ingestion, Egestion	Ingested 11% fewer algal cells Post capture or Post ingestion rejection Decreased reproductive output	Reproduction, respiration, energy	Cole et al. (2015)
Mammal	True's beaked whale *Mesoplodon mirus*	Polypropylene, acrylic, polyester	N/A	N/A	Uptake	Potential for trophic transfer through ingested prey	Digestive tract	Lusher et al. (2015)

4 Discussion

4.1 Microplastics as a sink or vector of pollutants

Partition coefficients, fugacity, and phase equilibrium are the measures used in scientific papers for assessment of the relationship between chemicals and plastics (Kwon et al., 2017; Silva et al., 2018; Hermabessiere et al., 2017; Luís et al., 2015; Wang et al., 2018). ScienceDirect (2019a) defines a partition coefficient as, “an empirically dimensionless property that describes how a chemical substance distributes itself between two phases." Fugacity is a component of the dynamics that determine the fate and transport of chemicals from microplastic particles (Kwon et al., 2017). ScienceDirect (2019b) states it is "a measure of a toxic chemical's tendency to escape from one phase to another." These two measurement properties understand how microplastics are a sink or a vector of hydrophobic organic chemicals (HOCs) and other pollutants (Kwon et al., 2017). Suppose the fugacity of chemicals is lower in the plastic phase than in water or organisms due to the longer attaining phase equilibrium. In that case, it is likely chemicals won't transfer readily between microplastics and an organism. Microplastics are more of a sink than a vector (Kwon et al., 2017).

Ziajahromi, Neale, and Leusch (2016) mention aged pellets can sorb chemicals more than virgin pellets due to the length of residence time in the ocean. Degradation of plastic surface areas increases the potential for sorb chemicals, which occurs with time (Brennecke et al., 2016; Silva et al., 2018). In addition to this, Ziajahromi, Neale, and Leusch (2016) note that the sorption and desorption of pollutants during the prolonged stay is dependent on the chemical levels in the surrounding water (Thevenon, Carroll, & Sousa, 2014; Ivar do Sul & Costa, 2014). Polyethylene (PE) typically has a higher sorption capacity compared to other plastic polymers for HOCs, followed by polypropylene (PP) and polystyrene (PS), according to Ziajahromi, Neale, and Leusch (2016) and Wang et al. (2018). This generally is in alignment with the results from the SQLR. Supposedly pigmented pellets can sorb chemicals more easily than clear or white pellets due to color additives and organic contents from plants and animals. Ziajahromi, Neale, and Leusch (2016, p.213) also state, "white pellets are present in seawater for a shorter time, resulting in low sorption and small specific surface areas." The surface area has a crucial part to play in the adsorption capacity of chemicals. Generally, the smaller the microplastic, the more surface area there is. This is consistent with findings (Brennecke et al., 2016; Frydkjaer, Iverson & Roslev, 2017; Avio et al., 2015; Luis et al., 2015; Tang et al., 2020).

4.2 Ecotoxicity of microplastics and pollutants on marine organisms

de Sá et al. (2018) produced a comprehensive graph of reviewed literature (59 papers) comprising the combined ecotoxicological effects of microplastics with other contaminants on different groups of organisms. PAHs were the most discovered pollutants causing effects amongst those papers. The most common polymer was PE, again aligned with this paper's results, followed by PS, PVC, and PP. Fish, Crustacea, Mollusca, and Annelida were groups of organisms. Of the effects mentioned, those that were aligned with results in this research include mortality, reproduction, genotoxicity, neurotoxicity, contaminant accumulation, hemolymph parameters, and behavioral outcomes (predatory performance). Biomarkers have been identified to determine the effects of pollutants in organisms (Landrigan et al., 2020). Amiard-Triquet, Amiard, and Rainbow (2013) define biomarkers as "a biochemical, cellular, physiological or behavioral variation that can be measured in tissue or body samples, or at the level of a whole organism that provides evidence of exposure and effects from chemical pollutants." While this research paper does not go into much biological detail, focusing on pollutants more so, indicators are essential to mention and understand. Kroon, Streten, and Harries (2017) outlined what they determined were the most suitable biomarkers to measure as "bioaccumulation markers, biomarkers of exposure (CYP1A, EROD, SOD, LPOX, HSP, MT, DNA strand breaks, micronuclei, apoptosis), and biomarkers of effect (histopathology, TAG: ST)". A few of these have been used as indicators in the literature sourced for this study. For example, histopathological alterations in the European sea bass's intestine were reported and changed on a cellular level (Peda et al., 2016).

Kroon, Streten & Harries (2017) discuss EROD (Ethoxyresorufin O-deethylase), CYP1A (Cytochrome P450 1A)/mRNA, and AHH (aryl hydrocarbon hydroxylase) as being significant sensitive biomarkers for fish in the liver. They mention EROD and AHH as a measure of catalytic response. AHH catalytic activity is used to measure reactions of CYP1A isoenzyme through the determination of benzopyrene. LPOX measures oxidative stress through the oxidation of polyunsaturated fatty acids. Lastly, CYP1A is very important for being responsible for the biotransformation of many pollutants discussed (e.g., PAHs, PCBs). (Kroon, Streten & Harries, 2017). Avio et al. (2015) examined *M. galloprovincialis* with PE and PS microplastics, adsorbed with pyrene. From the observed effects discussed in the results, Avio et al. (2015) demonstrated microplastics to adsorb PAHs, be bioavailable after ingestion, and have toxicological consequences from several molecular and cellular pathways. Significant or severe effects have been determined for this species of mussel from contaminated polymers, through physiological gut conditions (Avio, et al., 2015: Bradney et al., 2019; de Sá et al., 2018; Anbumani and Kakkar, 2018; Ziajahromi, Neale and Leusch (2016).

Frydkjaer, Iversen, and Roslev (2017), and Hermabessiere et al. (2017) both reported evidence on *D. magna*. Hermabessiere et al. (2017) mentioned PVC having an acute toxic effect but due to the phthalate content. In the case of Frydkjaer, Iversen, and Roslev (2017), PE microplastics were tested with phenanthrene and found PE to sorb less phenanthrene than the plankton themselves. They suggest due to the ratio of plankton to microplastics, vector effects pose less of an issue. Anbumani and Kakkar (2018) indicated that plastics associated with PCBs could accumulate in plankton.

Bezerra, Lacerda, and Lai (2019) conducted an extensive study on batoids (e.g., stingrays) through pollutants without microplastics. Batoids can accumulate many pollutants, including Hg, As, Pb, Cu, Cd, Zn, DDT, PCB, and PFAS. Due to the large number, they mainly focused on Hg. They also suggested using the biomarkers discussed, and others, to measure the effects of such pollutants. It is essential to evaluate this issue not just from microplastics and pollutants together, but individually. They can be damaging. However, the concern remains of how much. A conclusion can be drawn that is it varies depending on organism and situation. These pollutants also affect all trophic levels, which could potentially result in food chain accumulation (Lusher et al., 2015).

Lusher et al. (2015) conducted a study on the True's beaked whale. They suggested trophic transfer could have been the reason microplastics were found ingested. These whales' prey on mesopelagic fish, including lanternfish, which have been found to ingest microplastics before. Anbumani and Kakkar (2018) also mention a situation where the trophic transfer was observed from mussels to crabs. Lastly, it is essential to note organisms can experience different effects even in the same conditions, with the same species. Luis et al. (2015) did a critical study on juvenile *P. microps*, for L-est fish and M-est fish. Cr concentrations higher than 3.9mg/L caused oxidative damage in L-est fish, but not in M-est fish. Luis et al. (2015) pointed out that the two fish did come from different environmental conditions.

4.3 Plastics and non-additive pollutants as hazardous waste

Peda et al. (2016) tested polluted PVC pellets with adsorbed pollutants, including PAHs, hexachlorocyclohexanes (HCHs), DDTs, and PCBs with European sea bass. In Annex B of the Stockholm Convention, DDTs are restricted for production use unless for disease vector control purposes (Stockholm Convention, 2008a). PAHs are listed under Annex XV in REACH as a restriction proposal, and PCBs in the

Stockholm Convention (2008b) are banned from production, with the parties obliged to stop using this chemical. Any existing equipment with PCBs can be used until 2025, however. The European sea bass experienced moderate to severe ecotoxic effects relevant to polluted PVCs' exposure times at a cellular level and the distal part of the intestine. The pollutant contamination levels in this study by Peda et al. (2016) were not given, so the amounts required for consequences to occur are unknown.

Avio et al. (2015) mentioned PVC, PE, PP, and PS were demonstrated to have high sorption capacities of DDTs, PAHs, HCHs, and chlorinated benzenes. Wang et al. (2018) found that PE sorbs more high-ring PAHs than low-ring. As there are multiple PAHs present in the environment, this was important to determine. PP and PS also had more of an affinity towards high-ring PAHs. HCHs are not as easily partitioned to microplastics. Wang et al. (2018) stated the hydrophobicity of these substances is in the order of HCHs < PCBs < DDTs < PAHs. This provides more evidence for polymers to act as sinks for these substances. However, Hermabessiere et al. (2017) mentioned additives were more easily vectors from polymers than chemically bound. Supposedly marine biota would experience more of a ‘cleaning effect’ with HOCs than plastic additives. Nobre et al. (2015) tested embryos of *Lytechinus variegatus* against virgin plastic pellets and stranded pellets. They found that virgin pellets had more toxic effects than stranded pellets in the water for longer times. Nobre et al. (2015) concluded from this that plastic pellets do act as a vector for additives from virgin pellets. Variable toxic effects from stranded pellets were related to varying concentrations of HOCs adsorbed from the environment.

Hermabessiere et al. (2017) rated the octanol-water partition coefficients (Log Kow) for plastic additives. Several of these phthalates are listed in REACH and classified as CMR or endocrine disruptors. This is a significant concern, and alternative substances used in plastic production must be used to avoid any potential harmful impacts on marine organisms (ChemSec, 2019). Hermabessiere et al. (2017) mentioned phthalates are used to soften plastic and are mainly found in PVC.

4.4 Limitations of research and knowledge gaps

Bakir et al. (2016) suggest harmful physical effects on wildlife from ingesting large plastic items are well known. However, the ecotoxicological results are not as clear. This appears to be a consensus amongst researchers (Bakir et al., 2016; Thevenon, Carroll & Sousa, 2014; Bradney et al., 2019; Seltenrich, 2015; Gallo et al., 2018). Thevenon, Carroll, and Sousa (2014) concluded that long-term exposure to plastic and the combined mixture of plastic components' ecotoxicity is poorly understood. They suggested future research is necessary for understanding the effects of adsorbed pollutants and additives in higher trophic levels. Bradney et al. (2019) also agree this research is necessary. The lack of research could be because determining the effects is very difficult at present (Bradney et al., 2019; Seltenrich, 2015). Seltenrich (2015) stated there was "no research that demonstrated the bioaccumulation of adsorbed pollutants." Seltenrich (2015) thought what needed to be determined was the extent and effects of the transfer of pollutants from plastics to organisms when ingestion occurs.

Luís Carlos de Sá et al. (2018) suggests, "effect studies on this issue may be biased towards particular polymers, without consideration of reported occurrence in organisms and the environment, estimated release to the environment and bioavailability." They also mention studies should include more of the typology of microplastics in their papers. The majority of documents and the results produced were based on 'lab realities' as categorized in the SQLR. Ziajahromi, Neale, and Leusch (2016) stated, "Microplastic concentrations in lab experiments are much higher than what is found in the actual environment. Thus, any reported physical injuries should only occur in microplastic heavy polluted areas". It is quite challenging to observe and test ecotoxicity in the natural environment. However, researchers should do their best to improve the accuracy of microplastic and pollutant concentrations when observing ecotoxic effects on marine organisms (Burns and Boxall, 2018). These authors are not alone in their views, with Burns and Boxall (2018) mentioning the mismatch between "particle types, size ranges, and concentrations of microplastics used in laboratory tests and those measured in the environment." They add this is essential for a proper analysis of the risks of microplastics in the environment for any introduced regulatory controls for making a difference.

Raju et al. (2018) and Gallo et al. (2018) were more concerned with understanding microplastics at the source and gaining more insight through data collection. Raju et al. (2018) took this concern from WWTPs. They mentioned methodological gaps needed to be addressed to improve accurate assessment of the microplastics from effluents and biosolids, and their interactions with toxic pollutants in WWTPs. Along with this comes the need to understand the degradation factors that alter microplastics during treatment stages (Raju et al., 2018). Gallo et al. (2018) believed that the quantity of plastics inputted into the ocean globally is mostly unknown. This requires quantification of input loads, sources, and originating areas.

This research comprised many topic components, including microplastics, ecotoxicity, plastic waste, pollution contamination, and marine biology. Given the findings of this research on plastic additives as a source of toxicity, this evaluation would have benefited from using more papers that included these components of plastic. However, for the aim of this review it was essential to evaluate how much of a role other pollutants and non-additives play when it comes to harmful impacts in marine ecosystems. The outcomes of the SQLR method would have also benefited from higher data input from more academic papers. Given the timescale of this project, the results were confined in this way. In mentioning this, this research results were substantial enough to compare issues and evaluate the reality of findings.

4.5 Future research recommendations

In order to address the limitations and knowledge gaps of this topic, several recommendations should be followed through in future research. Silva et al. (2018) suggests a, "comprehensive effort should be made to develop databases containing the different spectra of polymeric materials when subjected to some degree of biodegradation, thus ensuring all particles are accounted for when analysing environmental samples". This is due to the variances in polymers according to their interaction with the environment (Silva et al., 2018). Anbumani & Kakkar (2018) also follow this recommendation by stating instrumental analysis is required on realistic concentrations of any chemicals released from microplastics coinciding with their degradation.

Field and laboratory mesocosm studies should be continued in order to reduce the knowledge gap of determining the probability of microplastics as 'vectors' for pollutants. Mesocosm studies provide a link between field surveys and highly controlled laboratory experiments. Data from field studies will in turn assist in assessing any anticipated biological effects (enzymatic, reproductive, histological etc.) from indivdiual organism interactions, and the potential consequences in ecosystem dynamics (Anbumani & Kakkar, 2018). As this review has done, organisms at different trophic levels should be studied along with biomarkers for indications of harm.

This review focused on the general marine environment rather than any specific geographical location. However for a more detailed examination, in future any known highly polluted locations in the marine environment should be studied on a case by case basis with a full review collating the data and discussing the sites studied. Then any locations in a similar geographical location could be further analyzed, with the view to making recommendations for improved environmental management in those areas.

There are some studies that have focused on a particular water body using methodologies that would be useful to continue using in future research in this field. Varotsos et al. (2020) chose Lake Sevan for their research, and used an algorithm for big data processing based on the geo-ecological information modeling system (GIMS) to monitor water quality. Lake Sevan was chosen as monitoring is necessary due to the rivers intersecting the lake carrying industrial, agricultural, and domestic waste which affects the water quality (Varotsos & Krapivin, 2019). GIMS uses a combination of models with big data fluxes to predict the observed evolution of the environmental system under consideration. The functions can be adapted to suit the chosen ecosystem taking into account existing and delivered information (Varotsos et al., 2020; Varotsos & Krapivin, 2019; Varotsos & Krapivin, 2018; Varotsos, Krapivin & Mkrtchyan, 2019).

This is useful for assessing the biocomplexity of marine ecosystems, its interaction with the surrounding environment, and the survivability (Varotsos & Krapivin, 2019). Varotsos, Krapivin & Mkrtchyan (2019) state this new tool and other optical tools that are similar are "proposed for the real-time diagnosis of water quality without traditional sampling and laboratory physico-chemical analysis". Other tools exist for water quality diagnostics such as in-situ and satellite observations, or water sampling and chemical analysis, and these are used in conjunction with a GIMS system particularly for more spatially distributed areas and complex data sets required (Varotsos, Krapivin & Mkrtchyan, 2019).

5 Conclusions

Microplastics have been identified as both a sink and a vector for pollutants. However, for non-additives and contaminants, whilst they can harm individual organisms, they may pose more of a threat singularly than adsorption in microplastics. The process of which plastic adsorbs contaminants is complex and dependent on many factors. These factors are mainly plastic-type and composition, original transport location, the level of pollution in the water at present, environmental conditions, and the interacting elements.

This research concludes plastic additives and microplastics to pose a threat to marine organisms, as indicated by biomarkers and findings in the literature. Certain non-additives are more ecotoxic than others according to their classification and evidence of harm to identified organisms. Through the method of classifying hazards, pollutants can be better understood when evaluating harm to marine organisms with and without microplastics. Generally, the smaller the plastic, the more toxic to aquatic organisms in terms of bioaccumulation and food chain effects. In some cases, trophic transfer was observed when organisms consumed prey that had ingested microplastics and retained them, more than they egested them. This has been demonstrated in laboratory conditions and some natural cases. Judging by the range of organisms evaluated in different trophic levels, trophic transfer from prey consumption seems plausible.

Different polymers have an affinity towards specific hydrophobic pollutants more than others. PP, PE, PS, and PVC were the majority observed and reported to harm marine organisms. However, some authors mention these are not the majority of microplastics found in the environment. This depends on the geographic location, but textile fibers and fragments are under-researched, mainly as they are found in large quantities in the water column.

This overview has obtained the information sought after for the aims and objectives. The research contributes a review of organisms at different trophic levels, as well as their interactions with major pollutants. It is recommended for research to continue in this area, using more accurate environmental concentrations. International bodies should consider re-evaluating hazardous and plastic waste regulations to establish improved solutions for mitigating their entry into sensitive marine ecosystems.

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