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Primary microplastics in the marine environment: scale of the issue, sources, pathways and current policy

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EXECUTIVE SUMMARY

The world's population has been growing at an unprecedent rate, so has the production and per capita consumption of plastics around the world. With approximately half of the world's population residing in coastal areas concerns have been raised regarding plastic pollution in the marine environment. Micro-plastics (<5 mm) (primary or intentionally added and secondary) are the major component of the marine plastic waste. While the impact of macroplastics in the marine environment has been well researched, the impacts, sources and pathways of microplastics in the marine environment need to be further addressed.

Microplastics have been shown to have negative impacts on the marine environment, through the reduction in growth, feeding rates and survival of marine species. Microplastics have been found in a large array of marine organisms, from filter feeders to mammals. Plastics can also act as a vector for heavy metals and toxins. Due to their microscopic size, microplastics can be assimilated by filter feeders and planktonic organisms and can be passed up the food chain, and into human consumption. Despite the vast amount of research undertaken to date, the impacts of microplastics on human health is currently poorly understood and require further investigation.

This paper analyses the research on microplastic pollution, why it is such a problem and what are its sources. It specifically focusses on intentionally added microplastics. Intentionally added microplastics can come from a large array of sources such as: industrial and domestic cleaning products, medicines, synthetic clothing, personal care and cosmetic products (PCCPs), construction materials and car tyres to name but a few. Some studies have reported that over 50,000 microplastic particles can be found in one gram of PCCPs product and as many as 17,700,000 fibres can be released during single washing cycle of 5kg.

The majority of microplastic marine pollution has been attributed to terrestrial sources (~98%). This paper reviews the pathways that cause microplastic pollution in the marine environment. Several potential and possible pathways have been identified, which include but are not limited to: sewage, rain and storm water runoff, wind transport and treatment of animals in aquaculture and farms. However, many of these pathways have not been quantified in relation to their magnitude and relative contribution. Waste water treatment plants (WWTPs) are believed to be one of the major pathways of microbeads and microfibres to the environment. Even with modern treatment processes it has been estimated that about 65 million microplastic particles still enter the environment daily in Glasgow alone. WWTPs have been estimated to account for 37% of all microplastic pollution in the ocean, while road run off, through tyre wear, is believed to account for 44%. Significant further research is needed to quantify the amount of microplastics entering the marine environment via the various pathways to develop mitigation strategies to prevent their dispersal.

This paper also reviews the policies that address microplastic pollution in the European Union (EU), the United States (USA) and Australia. The EU is a leader in the development of plastic pollution policies, and in particular, intentionally added microplastics. The EU is a unique political hybrid because it is not a state, but has state-wide qualities like a federal political system. It provides a useful framework for understanding how this issue can be addressed by a federation such as Australia. The USA has been in a leader in enacting regulatory measures to prohibit microbeads from personal care products and various states are developing laws to reduce microfibre pollution. The review of Australian plastic pollution policies finds that there is a current gap in addressing intentionally added microplastics.

1. BACKGROUND

This background paper was developed in the context of the NESP Marine Biodiversity Hub Project E3 – *Microplastics in the Australian Marine Environment* (2020). The project objectives are:

1. A literature review to identify key marine microplastics research and policy development internationally, with a focus on research that is contextual to microplastics in the Australian marine environment.

2 From this literature review, an options paper will be developed to explore the most feasible and impactful policy approaches for the Australian context to reduce microplastics in the marine environment.

3 These two reports will form the basis of a one day workshop that will draw together policy-makers, researchers and relevant industry peak bodies to discuss and recommend policy and other options to limit the release / impact of microplastics in the environment. A workshop report will be drafted to summarise findings, recommendations, and next steps (including identifying gaps in both science and policy will inform any future work required).

This background paper presents analysis of 155 peer reviewed academic papers, government reports and non-governmental publications addressing the topic of intentionally added microplastics.

2. INTRODUCTION

Over the last two decades the serious issue of plastic pollution entering the environment, including marine environment, has been a focus for research, policy, media and public concern [1-4]. The world's population has been growing at unprecedented rate, increasing by more than 45% in 30 years (from 1990 at 5.3 billion to 2019 at 7.7 billion) and predicted to reach 11 billion people by 2100 [5-7]. It was estimated in 2010, that over 2.5 billion metric tons of solid waste was generated by the world's population [2]. Over 10% of this waste consisted of plastic, which means we use approximately >275 million metric tons of plastic per year [2, 8, 9]. According to Andrady [8] per-capita plastic consumption has also been increasing.

Approximately half of the world's population resides in close proximity to the coast [2, 6, 10], and in 2010 it was found that this population contributed to between 1.7 and 4.6% (4.8-12.7 million metric tons) of plastic waste [2]. General waste that is sourced from the land ends up in the marine environment via sewage sludge, drainage, storm water runoff and other pathways. Approximately 80-85% of litter found in the ocean is plastic [4] and only ~5% of this plastics has been recovered [11].

Plastic litter has been divided into two primary categories: macro and microplastics. The exact definitions vary among studies, however, generally speaking microplastics are defined as particles <1 mm in size, while macro are defined as particles >1 mm [12, 13]. The accumulation of microplastics in marine environments has been reported all around the world, including protected areas; remote, populated islands and remote polar regions, with some locations having greater concentrations of microplastics than larger plastic debris [4, 9, 14-21]. Microplastics have been found in the great depths of the ocean, such as the Mariana and Japanese Trenches [22-24].

Microplastics are often further classified into primary and secondary source microplastics. Secondary source microplastics arise from the breakdown of the larger plastic items due to corrosion, breakage and degradation. Primary source microplastics, that include "intentionally added microplastics", are particles and fibres that have been purposely added to a variety of products, either for their direct properties (e.g. corrosive properties in cleaning products) or to enhance properties of other materials (e.g. strength in concrete, elasticity in textiles) [1, 25, 26]. However, there are discrepancies in the definitions used among authors [12], especially for some types of microplastics. For example, some authors identify fibres in textiles as primary microplastics [1, 4], while others place them into secondary microplastics category [8]. It can be argued that release of microplastics from textiles is due to wear and tear, which would fit the definition of the secondary microplastics. However Boucher and Friot [1] define primary microplastics as those "that can be directly released into the environment, as small particles", as opposed to from degradation and break down, which would in turn place fibres in textiles into primary category. It can also be argued that most microplastics get released due to use, as microplastics in the cosmetics are unlikely to get released until cosmetics, for example, are applied and washed off.

Similar confusion may occur when defining fibres in textiles as intentionally added or not-intentionally added. Textiles primarily made from plastic polymers may be considered a plastic product entirely, however fibres in the textiles where only a certain proportion of fibres have been added to either lower the cost or enhance some properties (e.g. elasticity) can be considered “intentionally added” microplastics. Due to these issues, Browne [12] has proposed to abandoned the use of adjectives in describing the sources of microplastics and use their origins for this purposes. He has identified four types of sources in his review: large plastic litter, cleaning products (that included beauty products), medicines and textiles. Here, we will predominantly focus on microplastics that are commonly identified as “intentionally added”, as well as a subset of microplastics that can be released into the environment as small particles due to use and wear (e.g. textiles, tyres), therefore partially adopting Boucher and Friot [1] definition. We will also further expand on the types of sources identified by Browne [12] by including sources such as construction materials and tyres; and subdividing cleaning products into actual cleaning products and personal care and beauty products categories.

It has been estimated that about 65 million microplastic particles get released into River Clyde, Glasgow on a daily basis just from one wastewater treatment plant, with majority of these particles being intentionally added [27]. High volumes of intentionally added microplastics released into the environment have also been reported for USA [28] and Europe [9]. Large volumes of microplastics added to the environment are of concern due to the high potential for a large array of negative impacts on marine ecosystems and human health [29-32].

3. INTENTIONALLY ADDED MICROPLASTICS: WHAT IS THE PROBLEM?

The impacts of plastic debris on the marine life have been widely recorded [29-31]. The entanglement and ingestion of large plastic items that lead to increased mortality for many species have been identified early on [33-35]. The earliest record of plastic ingestion by seabirds was made in the late 60s [36]. Back then, even in remote areas, up to 75% of albatross chicks had plastic discovered in their guts [36], today this number sits at almost 100% [37]. The literature has been fast growing since then, showing ingestion in several hundreds of species, including sea turtles and marine mammals [34, 38]. There have been many studies demonstrating that plastic ingestion by birds leads to slower growth and earlier mortality [39-41]. However, mortality of sea birds is linked to the amount of plastic ingested [38], rather than the toxicity of ingestion [42].

While the impacts of macroplastic are visual and often graphic, the impact of microplastics are less obvious. However, over 90% of floating marine plastic litter are microplastics [43], which can be more easily ingested by a larger array of species: zooplankton [44], worms [45], mussels [46-48], crabs [49, 50], fishes, sea turtles [44, 51] and marine mammals [52]. Apart of the direct consumption of microplastics, trophic transfers have also been demonstrated [53].

In 2016, Rochman et al. [34] reviewed 366 cases of perceived impacts of marine debris and identified that over 82% of those impacts were attributed to plastic, with a substantial majority being associated with microplastics of various origins. Microplastics' impacts often act at suborganismal levels (e.g. cellular), and while they are less graphic, they carry significant lethal and sublethal consequences [35, 54]. Studies have demonstrated that ingestion or absorption of microplastics can have substantial negative impacts (reduction in growth, feeding rates, survival) of ecosystem engineers [13]. They also have been linked with pathological and oxidative stress, reduced feeding and growth, reproductive issues and others negative impacts in many marine organisms [52, 54, 55]. Plastics have been shown to penetrate the blood-to-brain barrier in fish and lead to behavioural abnormalities [56].

In addition to the direct impacts caused by microplastics, studies show that they can act as a vector, transporting harmful chemicals through the food chain [37, 54, 55, 57-59]. One of the common sources of microplastics pollution is associated with anti-fouling paints [15, 60]. These paints often contain heavy metals, such as copper (Cu) and zinc (Zn), as well as other trace elements, such as barium (Ba), cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb) and copernicium (Cn), which can leach into the marine environment from paint flakes [61, 62]. Some of these elements are classified as biocides and can lead to significant negative impacts to marine communities [62, 63]. Plastics contain at least 4% of chemical additives, but they are also known to absorb toxins from the surrounding environment, including persistent organic pollutants and heavy metals, which allows those toxins to be transported through the food chain [8, 37, 55, 57-59, 64-66].

There is also evidence of microplastic contamination of commercially important marine species, which leads to the transfer of ingested microplastics into human consumption [67-71]. While the magnitude of the threat and the impact on human health is largely unknown and encourages debate [70-73], there is a growing plethora of literature that shows significant negative impacts on marine ecosystems [35]. While data on the human intake of microplastics from marine sources is limited [72], there is evidence of microplastic prevalence in products designed for human consumption of terrestrial origin [74]. Current lack of evidence should not be the reason for disregarding potential threats or for taking action to prevent that threat from occurring. Despite a significant growth in the literature highlighting the detrimental impacts of microplastic on marine environments these materials are still not classified as hazardous, impeding policy makers ability to regulate their production and release [35].

4. SOURCES

Since the early discovery of plastics in the mid to late 19th century when it was largely used to replace natural products, such as ivory, plastics have been incorporated into most aspects of our daily life [75-77]. Some of the common types of intentionally added microplastics are polyethylene, low density polyethylene and polyvinyl chlorides [9, 25], as well as polyester, polypropylenes and polyamides [78, 79]. There is a large variety of materials where intentionally added plastics are used for various purposes (Fig. 1).

4.1 Beauty and personal care products

Small plastic particles, often marketed as “micro-beads” and “micro-exfoliates” have been used in a large variety of beauty and personal care products, such as facial cleansers, toothpaste, bath and shower gels, and hand and face exfoliants, since the first patent for using microplastic scrubbers was developed 40 years ago [80-82]. These plastic beads have been used for their gentle abrasive qualities, as a replacement to natural products, such as seeds, ground nuts, oatmeal, pumice and others. Microplastic particles have also been added to cosmetic products, such as blushes, foundations, eye shadows and mascara, often due to the large variety of colour options available and shiny, glitter-like qualities [80, 81, 83].

While in mid-1990s microbeads and microplastics in cosmetics have been considered as a minor source of marine pollution [84], in the last quarter of a century the use of various personal care and cosmetic productises (PCCPs) have dramatically increased, and until recently, an average consumer would use PCCPs with added microplastics on a daily basis [81]. Fendall and Sewell [81] investigated four water-based facial cleaning products from four different commonly used, affordable and widely available brands in New Zealand. The products were manufactured in Germany, France, Korea and Thailand and contained polyethylene particles that widely ranged in size, shape and colour. The size of the microplastic particles varied from 4.1 to 1240 µm, with a large number of the particles in three of the four brands being less than 0.1 mm. Some brands also contained large beads designed to bust during washing into smaller particles [81].

In the recent years there has been a push towards phasing out and banning the use of microbeads in wash-off PCCPs, with New Zealand introducing such bans in 2017, one year after the UK [85]. However, the responses and actions are different for each jurisdiction [85] and much of more recent literature still reports many PCCPs to contain microplastics.

Lei et al. [86] examined a range of commonly used PCCPs, such as face and body cleansers and toothpastes in China and have estimated that 7.1% of face cleansers and 2.2% of body gels commonly used in China contain microplastics. Guerranti et al. [25] reviewed a range of literature that investigated microplastic additives in PCCPs. They found that the concentration of microplastics reported by different studies varied greatly reaching up to over 50,000 per gram of product, with around 1.85 g of facial scrubs and 10 g of body scrub estimated per use [25, 87]. The size of microplastics detected by the reviewed studies also varied with the smallest reported being 7-8 μm [25, 86, 88].

Up to 39 tons of microplastics attributed to some types of PCCPs have been estimated to be released into the environment in China per year [86]. Eriksen, Mason [89] detected high levels of microplastic contamination at several sites in the surface waters of the Laurentian Great Lakes, USA, with the highest abundance estimated to be up to 466,305 particles per square kilometre. Many of these particles were attributed to the PCCPs due to their shape and colour characteristics [89]. In Europe, up to 4.1% of the microplastic pollution has been assigned to microbeads in PCCPs products [83, 90]. East Asia and Oceania are estimated to contribute approximately 15% of primary microplastics to the environment, however this region contributes only 0.3% of microplastics attributed to PCCPs [1].

While the presence, quantity, size and common types of microplastics in the PCCPs have received a large amount of attention all around the world [25, 81-83, 91], there is still much uncertainty in how much these products contribute to marine pollution [83]. Similar to the possible underestimation of environmental contamination by microplastic fibres from the washing of clothing [9], there is evidence of substantial overall underestimation (up to ~80%) of microbead contamination [92]. The underestimation of microbead quantities was largely linked to bead characteristics, such as colour and size, rather than grain size of the mixed in sediment [92].

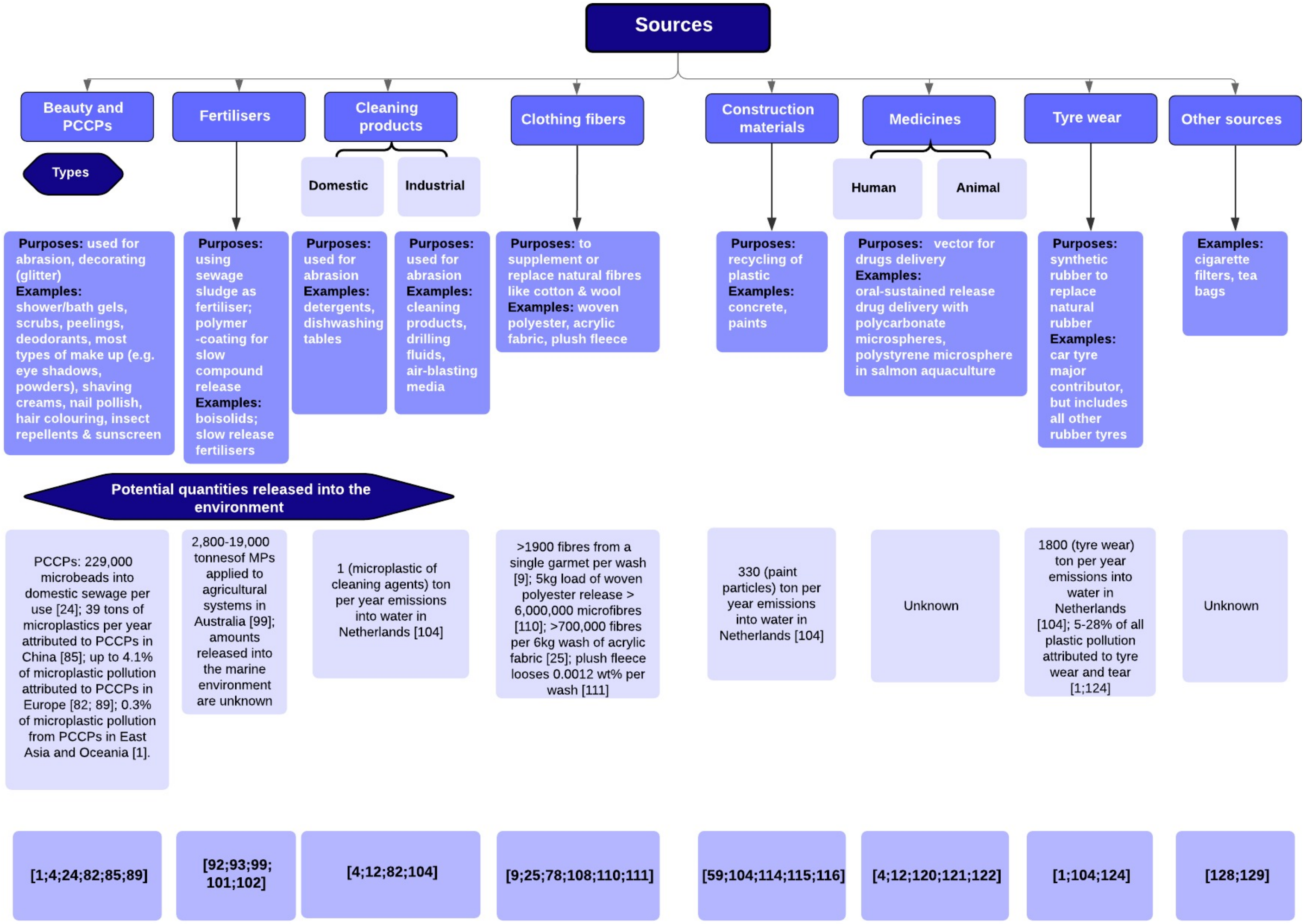

Figure 1 Sources of primary and intentionally added microplastics in the marine environment. The chart was created using Lucidchart.com

4.2 Fertilisers

Biosolids are a large source of microplastics in the marine environment. Biosolids are a mix of water and organic matter resulting from the sewerage treatment processes. Sewage sludge, in the form of biosolids, is then frequently used as a fertiliser in agriculture, directly or after composting [93, 94]. Australia produced an estimated 2.3 million tonnes of wet biosolids in 2019, with 67 per cent of biosolids used in agriculture, 16 per cent used in land rehabilitation and 8 per cent in landscaping (compost) [95].

Soils that had sewage treatment applied to them have been shown to contain elevated levels of synthetic fabric fibres compared to untreated sites [96].

Microplastics associated with the sewage sludge can then enter the marine environment via water runoff and wind pathways [27, 70], however quantifying these pathways can be difficult and hence data is scarce. Moreover, in Australia one per cent of biosolids produced are discharged directly into the ocean [95].

While some waste water treatment plants do remove a large amount of microplastics from the waste water (up to 99%), due to the sheer volume of microplastics contamination, a significant amount of microplastics can be retained in the sludge despite modern treatment processes [97, 98]. Due to these factors, waste water and sewerage treatment have been identified as a significant vector for microplastics entering estuarine or marine environments [see for example, 93, 99].

The issue of micro or nano plastics contamination in biosolids is an emerging area, and one where further research is needed [99]. It has been estimated that between 2,800 and 19,000 tonnes of microplastics could be applied to Australian agricultural systems through application of biosolids [100], with comparator estimates for the United States of between 44,000 and 300,000 tonnes per year and the European Union of between 63,000 and 430,000 tonnes [100]. Research on selected plastics in biosolids from a Queensland WWTP suggests a "total plastic concentration of between 2.8 and 6.6 mg/g dw (median = 4.1 mg/g dw) in Australian biosolids" [101].

Biosolid use is regulated by Australian states, with different standards applied across jurisdictions, with the Australian and New Zealand Biosolids Partnership having identified benefits in developing standardised guidelines. While the use of biosolids is strictly regulated to manage chemical loading on soils and to limit contamination, current regulation focuses on metals and synthetic compounds rather than on micro or nano plastics.

Another source of intentionally added microplastics in the marine environment comes from polymer-coated slow controlled compound release particles, generally referred to as nutrient prills. Nutrient prills can be used for controlled release of fertilisers. Conventional fertilisers have been associated with low nutrient assimilation by crops, increases in fertiliser production and high material losses, hence nutrient prills with their controlled, gradual (3-18 months) fertiliser release have been advocated for [102-104]. Additionally, polymer containing particles can also be used as biocides and herbicides [105]. However, whether all of these materials can be classified as microplastics has not been fully investigated. Furthermore, what the quantity of microplastics is in these materials and quantity of microplastics reaching the marine and aquatic environments from these sources has not be quantified [102] and requires further investigation.

4.3 Cleaning products

Microplastic particles are often added to a large variety of industrial (e.g. drilling fluids, air blasting media) and domestic (e.g. cleaning detergents) cleaning products, for abrasion [4, 12, 80, 84, 106]. For over 30 years surfaces have been cleaned using media containing acrylic, melamine or polyethylene particles (commonly 0.25-1.7 mm), that are being discharged at a high speed over a surface [33, 80, 84, 107]. Blasting media that includes plastic is often advertised as more ecologically friendly, made from recycled material and is generally considered to be gentler and/or faster than other options when used for paint removal, wood blasting, aircraft and machinery cleaning and other tasks [84, 108]. However, as such media is often re-used until particle size is reduced to the level that functionality is affected this media can get contaminated by a variety of toxic substances (e.g. heavy metals) and can be classified as hazardous [59, 80, 84, 109]. As particles deteriorate during the cleaning process to more microscopic sizes or even to powder they become more easily transported by wind or water and, hence, can enter the marine environment carrying those toxic contaminants [80, 84, 107]. The proportional contribution to the marine microplastics from this source is unclear and requires further investigation [12].

4.4 Clothing fibres

A large number of modern materials contain microplastic fibres, with polyester textiles being particularly common, though many other synthetic materials such as acrylics, polypropylenes and polyamides are also used [78, 79]. During domestic or industrial washing process these materials get exposed to mechanical and chemical stressors, which leads to shedding of the microplastic fibres. Many washing machine filters are not specifically designed to contain all of the microfibers. In fact, a large proportion of sewage appears to be contaminated by microfibers that have been shed from textiles during washing cycles [9, 110]. Average fibres released during washing can be as small as 11.9 μm in diameter and 5 mm in length [26]. The micro and nanoscopic size of many of these fibres also prevents them from being contained by wastewater treatment plants [27, 111], leading to these microplastics being washed into the marine environment [9, 110]. Browne et al. [9] have identified washing of textiles, as one of the important sources of microplastic pollution in the marine environment. They have conducted a large scale study of 18 shorelines worldwide, investigating microplastic contamination in the sediment on those shores. Microplastic contamination in sewage-effluent was also examined in this study [9]. The results have demonstrated that the composition of the microfibers discovered in the sewage-effluent was similar to that found on the shores, consisting of 67% and 78 % of polyester, and 17% to 22% of acrylic, respectively. They have compared these proportions to the ones used in the textiles and those that have been shed during a washing experiment, and have concluded that a large proportion of the marine microplastic contamination must come from washing process [9]. Similar results have been reported by several later studies [110].

The washing cycle, detergent and softener used, and the type of the material are all responsible for the quantity of microfibers that are shed during washing [26, 79, 112]. Browne et al. [9] reported that a single garment can release more than 1900 microfibers per wash, with fleece being particularly susceptible to fibre loss. Napper and Thompson [26] investigated fibre release from three different material types: polyester, polyester-cotton blend and acrylic and have reported that polyester-cotton blend had the lowest rate of fibre loss during the wash, while acrylic had the highest [26]. They estimated that over 700,000 fibres can be released in a single wash of a 6 kg load. De Falco et al. [112] has reported that woven polyester released the highest amount of fibres during a wash, when compared to knitted polyester and woven polypropylene. They have also estimated that 6,000,000 - 17,700,000 fibres can be released from a typical 5 kg of polyester fabric and that the size of the fibres was too small to be effectively captured by wastewater treatment plants (the smallest diameter reported 19 ± 6 μm) [112].

Several studies that have investigated microfibres loss from textiles during washing process have reported that the loss of fibre decreases with repeated washes [26, 113], eventually stabilising at 0.0012 wt% for polyester fleece textiles [113]. The decrease in fibres loss with consecutive washes was influenced by the textile type, with acrylics showing the most rapid decrease, followed by polyester, while polyester-cotton blends showed little variability [26]. The size of the fibres (ranging 100 and 800 μm) released did not appear to change with repeated washing suggesting that fibre staple length has an influence on the amounts of fibres released [79]. Results on the use of detergents and softeners differed between studies. Napper and Thompson [26] reported a reduction in the shedding of microfibers when no detergent was used for blended textiles, however results were variable for acrylics and polyesters. Hernandez et al. [79] also reported reduction in fibre shedding when detergent was not used, however the type of detergent (liquid or powder) did not have a significant effect, while De Falco et al. [112] demonstrated that liquid detergent reduced fibre loss compared to powder. They also reported a 35% reduction in fibre loss when softener was applied, while Napper and Thompson [26] suggested that polyester-cotton blends shed more fibres with softener added and Pirc et al. [113] demonstrated no significant effect of detergent or softener on fibre loss. Pirc et al. [113] also showed that tumble drying caused 3.5 times higher fibre loss than the washing process.

As larger, bulkier items are usually worn in winter and domestic washing can increase up to 700% in colder months compared to warmer months, a higher microfibre release into sewage and consequently the marine environment is expected for those seasons and countries with colder climates [9, 114, 115]. Higher microfibre contamination is also predicted in habitats that are close to highly populated areas [9]. Microfibre loss during washing and contamination of the environment is expected to be underestimated, as colourless fibres are harder to identify and are potentially missed during sampling [9].

While some research has been conducted investigating microfibre marine and terrestrial habitat contamination through the washing of textiles via sewage effluent pathways, little is known about microfibre contamination and pathways into freshwater, marine and terrestrial habitats during production or use of such textiles [12]. Further research is required to investigate the primary sources and pathways of microfibre contamination. These include investigating the differences in seasonal and geographical variation in microfibre contamination; possible ways to reduce loss of the microfibres (e.g. type of washing cycle, detergents and softeners) during washing and tumble drying processes; and improvements of washing machine and wastewater treatment plants' filters to prevent release of this contamination into the marine environment [9].

4.5 Construction materials

With almost 50 million tons of plastic consumed in Europe in 2012 and over half of these plastics entering a waste stream, and about 40% of the later ending up disposed, it has been suggested that plastic waste could be recycled or upcycled in concrete mixtures to reduce waste [116]. While majority of these particles would come from breakdown of other plastic items, effectively being secondary plastics, through the process of recycling, adding these particle to concrete mixtures, they become primary or intentionally added microplastics. Many studies have investigated the properties of concrete with added plastic fibres or plastic aggregates [116-118]. Depending on the types of plastic particles added (e.g. polypropylene and nylon fibres) various properties of cement mortar and concrete, such as strength, can be improved [116-118]. Moreover, it is estimated that many types of common plastic can persist inert within concrete mixtures for extended periods of time (years to centuries) [116] and hence this approach may prove to be a viable option for recycling and containing plastic waste. However, no studies to date have investigated the recycling of concrete with plastic additives or possible release of plastic particles, including quantities and toxicity levels, into the environment during wear and tear or towards the end of product life [116]. Therefore, it is difficult to estimate the overall effectiveness of the proposed approach.

Paints are extensively used in many industries for esthetical reasons and for purposes of shielding and protection, including on the hulls of the ships [61, 62, 106]. The majority of paints do not contain plastic microbeads, however they do contain resins and, therefore, paint particles are classified as microplastics [106]. Some paints are used for anti-fouling on the ships hulls and may contain biocides [62]. However, due to the 2008 ban on the use of tributyltin in the antifouling paints, high tolerance of some invasive organisms to copper and increased marine pollution due to the use of biocide induced antifouling pains nontoxic options have been researched and implemented. Some of those include foul-release coating, when the paint layers are shed off the ship as it moves through the water [62], creating one of the pathway of paint particles into the marine environment. It has been estimated that 690 tons of paint particles get released into the environment in Netherlands, which is 99.5% more pollution than from abrasive cleaning agents which is estimated to be equivalent to about 3 tons per year [106]. From those 690 tons of paint associated microplastic particles per year, approximately 330 tons of paint particles per year have been estimated to be released into aquatic environments. Paint particles were also some of the dominant types of microplastic pollution detected around the south-eastern coast of Korea (~20-50% depending on collection method and season) [60]. The size of the released paint particles (flakes) can vary and can be < 1μm [60, 106]. Precise estimation of paint particle pollution in the marine environment is difficult, as paints can be used by professionals and consumers and can come from multiple sources, such as cleaning off old paints, tear and wear of painted surfaces, foul-release coating and through cleaning of painting equipment [106].

4.6 Medicines

Microplastic particles are used as a drug delivery vector of a large variety of drugs in human and animal medicine (terrestrial and aquatic) [12]. The microplastics can be injected, inhaled or taken orally and can be translocated from lungs or intestine into the blood stream [12, 119-121]. In fish aquaculture oral delivery of medication carries multiple benefits, such as convenience of handling and absences of stress to the animals that are being treated. Microplastic particles carrying antigens have been used in Atlantic salmon aquaculture [122]. In human medicine microplastic particles have been used to deliver anticancer, cardiovascular and other drugs [12, 123]. The use of the polymeric microspheres as delivery pathways of medication into the brain has also been widely explored [123, 124]. Browne [12] reports that a variety of polymers are used as vectors in medicine, ranging from biodegradable to longer lasting polycarbonates and polystyrenes. In the same work, Browne [12] also notes that there large gaps in knowledge of the types and sizes of the polymers used in medicines, as well as amounts and pathways of those microplastics into the marine environment.

4.7 Tyre wear

Microparticles that come from the wear of polymer based materials such as car tyres can also be classified as primary microplastics [1]. Modern tyres consist of natural rubber and synthetic rubber, which in fact is a plastic polymer [1, 125]. Verschoor et al. [106] has estimated that about 1800 tons of microplastic particles enter the environment from wear of tyres in the Netherlands. Global contribution of tyre wear and tear to marine microplastic pollution has been estimated to be around 10-28%, with car tyres being the major contributor [1, 126, 127]. The exact amount of microplastics released from tyre wear does depend on several factors, such as weight and type of vehicle, speed and road surface [1, 127]. Microplastics released from tyre wear can enter the marine environment via road and storm water run-off, wind pathways, as well as waste water treatment plants [1, 128]. Even though WWTPs may be expected to receive a substantial portion of the road run-off, the data on how much of the microplastic particles from tyre wear is present and how much gets removed by WWTPs is largely lacking [129]. While the release of microplastics from tyres is non-intentional, microplastic pollution from this source is highly under-researched, but substantial and, therefore must not be ignored [1, 127, 128], as currently there are few alternatives for tyre production. Further work is needed to quantify both tyre dust and its transport through WWTPs.

4.8 Other sources

A range of other possible microplastic pollution sources have been discussed in the literature, such as microfibres in the cigarette filters and plastic in teabags [106, 130, 131]. Hernandez, Xu [131] estimated that ~11.6 billion microplastics and 3.1 billion nanoplastics get released into a single beverage from a single teabag during brewing. These tiny plastics have a potential to enter marine environment via sewage pathways.

Wright et al. [130] has identified cigarette filters as one of the primary sources of coastal pollution. These filters contain microfibres (cellulose acetate) and a range of toxins, which can be taken up by filter feeding organisms and be passed through the food chain. While Wright et al. [130] found no significant negative impacts of cigarette filter microfibers on ragworms, they did find a substantial negative impact of the toxicants associated with those filters. Other studies have demonstrated negative impacts of microplastic uptake by a range of invertebrate species, including lugworms [45] and oysters [132], which indicate that impacts may be species specific.

Many of these additional sources have been poorly researched and, therefore, are poorly understood and quantified. The pathways of many of these sources into the marine environment have also not be carefully identified.

5. PATHWAYS

As with many types of marine pollution, the majority of microplastic pollution in the ocean comes from land based activities (~98%) [1]. Several pathways of microplastics into the ocean have been identified by earlier studies and include (but are not limited to): waste water treatment plants (i.e. sewage effluent and sewage sludge), rain water runoff, wind, and treatment of animals in aquaculture and farms [1, 12] (Fig. 2).

However, microplastics entering the marine environment have not been well qualified (i.e. types of microplastics) or quantified for the majority of these pathways. When attempts to quantify microplastic pollution from a particular pathway (most commonly waste water treatment plants) have been made – the data varied dramatically between studies, suggesting that primary pathways may differ between geographical locations and microplastic pollution sources [1, 12, 25, 27].

Guerranti et al. [25] has reviewed several studies that looked into the concentration of microbeads in PCCPs and have estimated that PCCPs can contribute to the introduction of over 200,000 microbeads to the sewage with a single use. Gouin et al. [28] has estimated that 263 tones/year of polyethylene microbeads get emitted in the USA alone, based on per capita product consumption. Modern waste water treatment plants (WWTPs) are believed to retain a significant amount of the microplastic particles that come from domestic and industrial waste water [27, 133, 134]. When primary, secondary and tertiary treatment is applied to the effluent the microplastic concentrations get reduced to 0.2 – 1.5 microplastics per litre, which is over 98% reduction from the initial effluent [27, 133, 134]. However, even with such significant reduction in microplastic concentrations in sewage effluent, when modern technologies are used, Murphy et al. [27] estimated that about 65 million microplastic particles still enter the environment daily in Glasgow via this pathway due to a large volume of effluent, which may be similar to other highly populated centres. In the USA, Rochman et al. [135] calculated that 8 billion microbeads per day enter the aquatic environment via WWTPs.

There are many difficulties associated with distinguishing and quantifying microplastics in the sewage effluent due to their variable properties, like size and shape, which may lead to underestimation of microbeads pollution from WWTPs [12]. Moreover, filters on WWTPs are often not designed to retain microfibers due to their size and other qualities and hence sewage may be one of the primary pathways of microfiber pollution into the marine environment [12]. Indeed, in the pioneering study, Browne et al. [9] sampled replicate sewage disposal sites and reference-sites and found that disposal-sites had significantly higher microfibre concentration than reference sites (by >250%). More recent studies have also reported fibres being one of the most common microplastic type retained in the effluent even after application of the modern treatment practices [134]. While WWTPs have been estimated to be responsible for approximately 25% of global microplastic pollution (land and sea), 71% of this waste is predicted to end up in the marine environment, accounting for approximately 37% of all microplastic pollution in the ocean, making it one of the primary pathways [1]. Road run off is estimated to contribute 44% to the total marine microplastic pollution, when wind and ocean based pathways are estimated to contribute <20% [1].

Despite over two decades of research into the microplastic pollution in the marine environment, many pathways have not been identified or quantified. Little is known about pathways in the marine environment of microplastics used in domestic and industrial cleaning products, medicines or other sources from use, production and end of life scenarios. Substantial further research is essential to identify primary pathways of microplastics into the marine environment, quantify amounts of microplastic pollution contributed by each pathway and identify primary sources of the microplastic waste transported by those pathways [12] (Fig. 2).

6. INTENTIONALLY ADDED MICROPLASTICS: THE EUROPEAN UNION

6.1 Overview

The European Union (EU) has the most advanced framework related to intentionally added microplastics. This includes addressing the problem in relation to action plans and framework directives to guide and direct member states responses, consultations and engagement with industry, governments and community and timelines for action. While the EU has advanced discussions on and responses to microplastic pollution, issues remain related to categorisations, definitions and management of the problem [136]. At the same time there is a small but significant literature assessing the policy and regulatory issues [for example, 102, 137, 138, 139] related to intentionally added microplastics.

The EU has the European Strategy for Plastics in a Circular Economy (2015), a Directive on Single-Use Plastic, the Eco-design Directive and various other waste management and prevention strategies. It is seen as a leader because of its plastics pollution policies and by enforcing the ‘polluter pays’ principle which puts the responsibility back onto industry. The European Strategy for Plastics in a Circular Economy also includes measures against single use plastics and fishing gear; restrictions related to the use of microplastics in products or measures against microplastics generated during the life cycle of products; measures to reduce marine litter from ships, including fishing vessels and recreational craft.

The EU’s Action Plan for the Circular Economy was adopted in 2015 and the Waste Framework Directive (WFD) entered into force on 4 July 2018. The WFD provides a broad framework for action on plastic pollution including work by EU agencies such as the European Chemicals Agency (ECHA) to develop key data bases. The EHCA (following a request from the European Commission) or a member state or states, can propose a restriction on the use of substances. A proposal is being developed by the ECHA “Restricting the use of intentionally added microplastic particles to consumer or professional use products of any kind.”

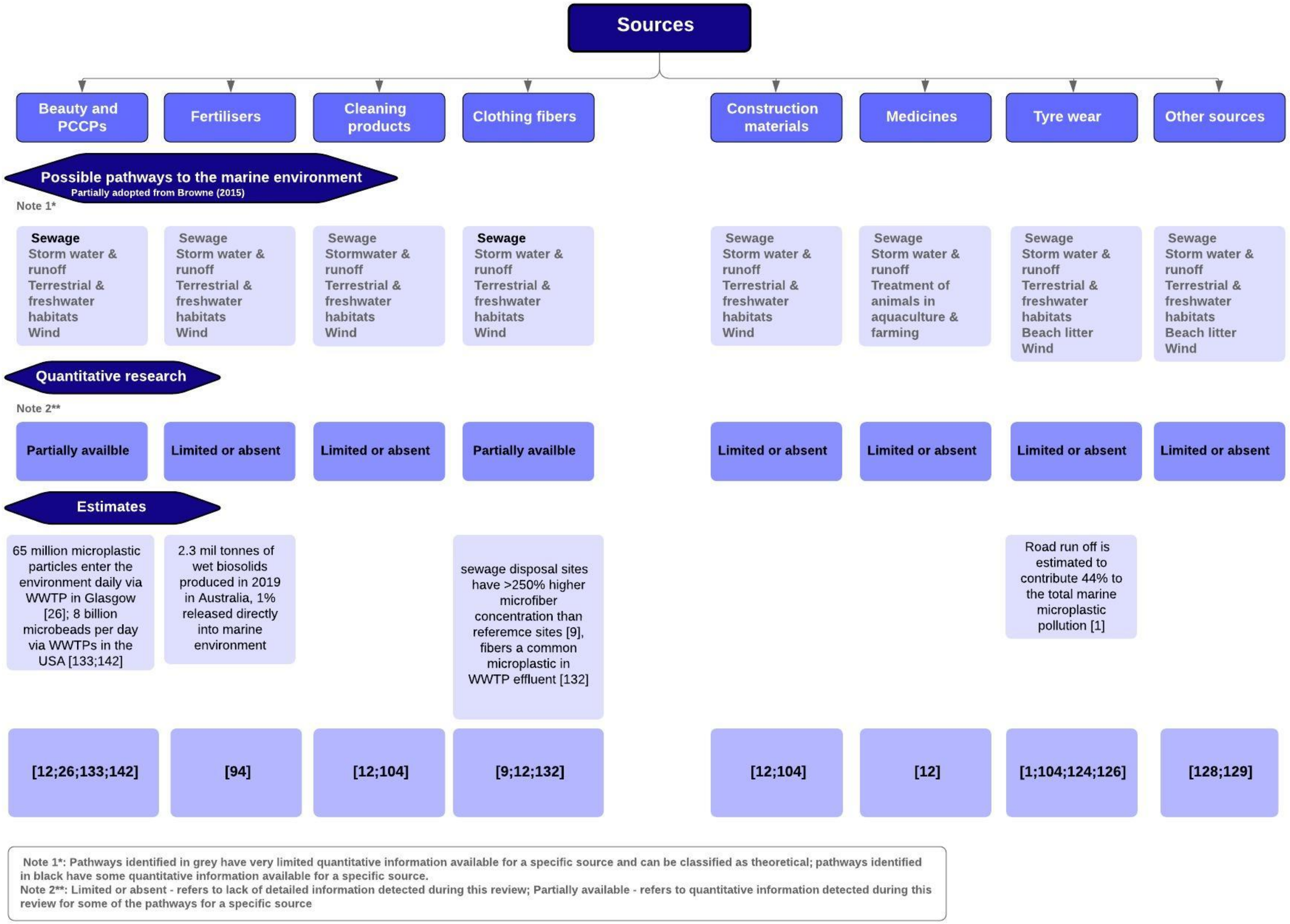

Figure 2 Pathways of primary and intentionally added microplastics in the marine environment. The chart was created using Lucidchart.com

6.2 Current policy proposals

The “ECHA has submitted a restriction proposal for microplastic particles that are intentionally added to mixtures used by consumers or professionals. If adopted, the restriction could reduce the amount of microplastics released to the environment in the EU by about 400 thousand tonnes over 20 years” [140].

The ECHA’s proposed restriction targets intentionally added microplastics in products from which they will inevitably be released to the environment. The definition of microplastic is wide, covering small, typically microscopic (less than 5 mm), synthetic polymer particles that resist (bio)degradation. The scope covers a wide range of uses in consumer and professional products in multiple sectors, including cosmetic products, detergents and maintenance products, paints and coatings, construction materials and medicinal products, as well as various products used in agriculture and horticulture and in the oil and gas sectors [140].

The proposed restriction emphasises the breadth of the use of intentionally added plastics and the challenge in developing appropriate policy responses. The ECHA’s work has raised a number of issues that centre on the management of intentionally added plastics. The management of microfibres produced from the recycling of plastic water bottles into new products is well known. A less well recognised area potentially affected by the proposed restriction was the use of plastics forming the basis of artificial sports fields or pitches. Such products deemed to be exempt from the proposed restriction but highlight the challenges of recycled plastics as a potential future problem.

The EU process provides a good basis to policy learning, and the deep and broad industry consultation that is embedded in such processes is noteworthy.

7. INTENTIONALLY ADDED MICROPLASTICS: THE UNITED STATES OF AMERICA

The United States has enacted regulation on microbeads on national and state levels, and there has been some regulatory action on monitoring microplastics in drinking water and reducing the discharge of microfibres. In 2014, Illinois became the first state government to prohibit the sale of rinse-off microbead products. Other USA states followed suit and eight states had either prohibited or limited the sale of such products by the end of 2015 [141]. The Illinois legislation has been criticized for being too ambiguous in its definitions [142]. The California Microbead Bill no.888 was passed in 2015 and it was intentionally designed to be clearer in its definitions than the Illinois Bill. It prohibits the selling or offering for promotional purposes any personal care products with microbeads as of 1st January 2020.

The USA Federal government passed the Microbead-Free Waters Act of 2015 which prohibits the production (as of 1 July 2017) and sale (as of 1 July 2018) of rinse-off microbead products. The USA Act was modelled on the California Bill but it does not address the removal of microbeads from aquatic environments, nor does it address other microplastic pollution. It also overrides state law definitions [85]. The Act has been criticized due to its sole focus on microbeads, the exclusion of other sources of microplastics [143] and that it lacks a set standards [142]. However, it was estimated that the Act has prevented more than 2.9 million pieces of microplastic from entering aquatic environments each year [144].

The California Senate Bill 1263 ‘Ocean Protection Council: Statewide Microplastics Strategy’ enables the council with the State Water Resources Control Board (SWRCB) and the Southern California Coastal Water Research Program to develop, adopt and implement a statewide establish a Statewide Microplastics Strategy that is to be submitted to the Legislature by the end of 2021 [145] and to be implemented by December 2024. This Strategy aims to standardize methods “for monitoring microplastics in drinking water, surface water, sediment, and fish tissue, and convene experts to better understand the human health and ecological effects” [146].

Connecticut was the first state that passed a law regarding microfibre pollution. *The Act Concerning Clothing Fiber Pollution*, House Bill 5360 was passed in 2018 and it established a working group which is to develop an education and consumer awareness program on synthetic microfibre pollution. The Act specifically requires representatives from the apparel industry to be part of the working group. California has a proposed Microfiber Bill AB129 that asks for the SWRCB to identify labelling standards for clothing manufacturers, standards for evaluating filtration systems. It also requires the installation of filtration systems in laundry systems both in public entities January 2020 and private entities that use industrial or commercial laundry systems to install a filtration system by January 2021 [147]. This bill failed to be passed on February 2020. However, the SWRCB is still working on other microplastic issues and it adopted an official definition of microplastics in drinking water in June 2020 that states:

‘*Microplastics in Drinking Water’ are defined as solid polymeric materials to which chemical additives or other substances may have been added, which are particles which have at least three dimensions that are greater than 1nm and less than 5,000 micrometers (µm). Polymers* *that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded* [148].

This definition will provide the basis for a long term approach to monitor and research microplastics in drinking water supplies.

Voluntary measures have also been taken in the USA to reduce microplastic pollution. For example, ‘Operation Clean Sweep’ is an international “voluntary stewardship” initiative administrated primarily by the Plastics Industry Association (PLASTICS) and the American Chemistry Council (opcleansweep.org) that aims to decrease the release of plastic pellets, flakes, and powders into the environment via collaboration with companies.

8. INTENTIONALLY ADDED MICROPLASTICS: AUSTRALIA

8.1 Overview

Australian governments have committed to reducing marine plastic waste. The Australian Government has worked with state governments, industry and community to address the reduction, reuse and recycling of plastic waste. In June 2018, the Australian Senate Environment and Communications References Committee recommended that the Australian Government establish a circular economy that is designed for the reduction, reuse/repurpose and recycling of plastic [149]. These actions are linked to the that provided targets and actions implementing the National Waste Policy 2018, as revised in 2019 [150].

These include:

- ban the export of waste plastic, paper, glass and tyres, commencing in the second half of 2020
- reduce total waste generated in Australia by 10% per person by 2030, and linking to programs such as the NSW Marine Estate Management Strategy initiative on 'improving water quality and reducing litter'.
- 80% average recovery rate from all waste streams by 2030
- significantly increase the use of recycled content by governments and industry, through programs such as the NSW state container deposit scheme
- phase out problematic and unnecessary plastics by 2025
- halve the amount of organic waste sent to landfill by 2030
- make comprehensive, economy-wide and timely data publicly available to support better consumer, investment and policy decisions [151]

The Commonwealth *Environment Protection and Biodiversity Conservation* Act (1999) lists the threatened marine species that are affected by marine debris including plastic. It is supported by the recently updated 2018 *Threat Abatement Plan for the Impacts of Marine Debris on the Vertebrate Wildlife of Australia's Coasts and Oceans*. The plan recognises the impacts of plastics, and specifically microplastics on marine species and environment.

At the National Plastics Summit in Parliament House, Canberra, Monday 2nd March 2020, the Prime Minster committed government to a National Plastic Plan to be delivered by the end 2020.

8.2 Supporting Circular economy approaches

The Australian Packaging Covenant Organisation is a co-regulatory nongovernment organization that partners with the Australian Government and over 1,500 members industry with a goal of helping its industry-based signatories realize Corporate Social Responsibility

(CSR) opportunities and reduce plastic packaging waste [152]. The organisation has over 1,500 members and involves eight different government organisations [153]. The Covenant is an agreement between the Australian Government and state environment ministers that seeks to minimise the impact of packaging on the environment. It is also working towards the development of circular economy approaches with its members [Commonwealth 154].

The circular economy system in principle should retain resources within the economy, minimising resource depletion and waste [155]. The movement to a circular economy requires changes in not just manufacturing and packaging, but also significant modification in design and materials [156].

8.3 Microbeads

Australia has phased out microbeads in 'rinse off' cosmetic and personal care products. The phase out of 'personal care, cosmetics and some cleaning products', led by industry group Accord through its *BeadRecede* campaign, began in 2016 and was concluded in by mid 2018.

In late 2017, the Department commissioned an independent assessment of personal care and cosmetic products sold in supermarkets and pharmacies. The assessment found that of approximately 4400 supermarket, pharmacy and cosmetic store products inspected, 94 per cent were microbead-free. No shampoos, conditioners, body washes or hand cleaners were found to contain microbeads, indicating that the phase-out in these products may be successful [157].

The success of the microbead phase out provides useful insights for broader responses to the issue of managing intentionally added microplastics. The phase out was supported by broad based international action (Australia joined Canada, China, France, Ireland, Italy India, Netherlands, New Zealand, South Korea, Sweden, Taiwan, Thailand, the United Kingdom and the United States of America in banning microbeads rinse-off cosmetics). The Australian initiative was led by, and had support from industry; microbeads had ready substitutions or replacements; production and processing operations were not affected; and the phase out gained consumer support.

A key element of the microbead phase out was the *Voluntary Industry Phase-out of Solid Plastic Microbeads from 'Rinse-off' Personal care, Cosmetic and Cleaning Products Monitoring and Assurance Protocol* agreed between the Australian Government and Accord. This protocol released in December 2018 recorded actions to this date and 'outlines measures taken to date and details actions to June 2022 to support the continued success of the phase-out of microbeads and to ensure they do not re-enter the market through imports or new products'.

There is limited literature that directly focuses on legal and policy aspects of Australia's responses [but note 150, 152].

9. CONCLUSION

The literature reviewed in this paper illustrates the significance of intentionally added microplastics in a range of products. This paper reinforces the scale and scope of the problem and identifies some of the gaps in our knowledge. The use of microplastics in some of these products is linked to upcycling, reusing and recycling processes. As noted in this paper, intentionally added microplastics are found in cleaning products, medicines and pharmaceuticals, clothing fibres, personal care and cosmetic products, construction materials, and in a range of consumer products. The diversity of products, different production cycles, management of waste and gaps in knowledge provide challenges in developing appropriate policy responses to managing pollution from intentionally added microplastics.

Australia has successfully addressed the problem of pollution from microbeads in personal cleansing products, where active and engaged industry was able to look at the replacement and substitution of plastics, and clearly displayed capacity, ability, and readiness to implement change. It is also important that Australian Governments are aware of activities elsewhere. The paper draws on the work in addressing the problem of pollution from intentionally added microplastics in the EU. The work of the EHCA in developing a 'restriction' provides useful guidance but also highlights that any response needs to link government, industry and the community. This provides useful insights in developing policy options to address pollution from intentionally added microplastics.

Such options will need to:

- acknowledge the diversity of products and practices that incorporate intentionally added microplastics and
- the pathways for these microplastics to enter the marine environment.

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