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Microplastics and the Australian Marine Environment: Issues and Options

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EXECUTIVE SUMMARY

A key to addressing the problem of microplastic pollution is the identification of major sources and pathways of such pollutants. The paper centres on analysis of key sources: personal care, cosmetics, and cleaning products (PCCPs), synthetic materials (microfibers), tyres, fertilisers and biosolids; and key pathways that include wastewater and sewerage treatment plants. The paper outlines the current state of scientific understanding on these sources and outlines various options available to mitigate and manage the introduction of microplastics to the marine environment from these sources.

The paper examines current policy and strategies employed in the European Union as a benchmark for possible uptake into Australian policy followed by the examination of more mitigation and management approaches; focussing on circular economy approaches, product stewardship, extended producer responsibility, consumer behaviour and regulatory options. The paper concludes by outlining possible policy options for managing and mitigating impacts of microplastics in the Australian marine environment.

BACKGROUND

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

1. A literature review (Paper 1) of 155 peer reviewed academic papers, government reports and non-governmental publications to identify key marine microplastics research and policy development activities internationally, with a focus on research that is contextual to microplastics in the Australian marine environment, which was completed in July 2020.

2 An options paper (this report) developed from this literature review, which will identify feasible and impactful policy approaches to reduce microplastics in the marine environment for Australia.

3 The literature review and the draft options paper which supported a round table workshop bringing together policymakers, researchers and relevant industry peak bodies to discuss and recommend policy and other options to limit the release of microplastics in the environment. Due to COVID-19 restrictions, the roundtable was held online on 27 and 29 October 2020.

4 A round table workshop summary is provided as section 6 of this report and roundtable findings, recommendations and next steps (including identifying gaps in both science and policy to inform any future work required) are in Appendixes 1 and 2.

1. INTRODUCTION

Global human population has been growing at an unprecedented rate [1, 2], which has resulted in a shortage of many materials. Early plastics were discovered during a search for a replacement for ivory, previously used for the production of billiard balls [3, 4]. Over time, improvements in plastics technologies, development of inorganic plastics, reduced cost of plastic production, high flexibility of shapes and designs, and the high diversity of applications led to the rapid growth of the world's plastic production and consequently plastic environmental pollution [3, 5-7].

Despite recent efforts in managing global plastic pollution, it is estimated that 60-99 million metric tonnes of plastic waste was mismanaged in 2015. Four major options have been identified for plastic management, such as reduction, substitution, recycling and controlled disposal. Plastics that do not fall into one of these broad categories are considered mismanaged [8]. In other words, mismanaged plastic waste is identified as plastic that has been lost from the "management conveyor" and has the potential to enter the environment. For example, plastic in open dump sites and urban litter [8-10]. A significant proportion of this waste ends up in the ocean, with approximately 80-85 percent of ocean litter being plastic [11]. Microplastics, those plastic particles <5 mm in size, contribute to over 90 percent of floating marine plastic litter [12], with some locations having greater concentrations of microplastics than macroplastics [7, 11, 13-19]. High-income countries have been estimated to leak between 29 and 76 percent of microplastics into the environment and have been urged to address this loss as one of their priority actions [8].

Concerns about the impact of microplastics on the marine environment have been growing. Due to their microscopic size, microplastics are extremely bioavailable to a large array of marine organisms. They can be assimilated by filter feeders and zooplankton and they can pass through cell membranes and be absorbed by marine plants [20-25]. While our understanding of the impacts of microplastics on marine organisms is limited [26], studies have demonstrated that they have the potential to reduce growth, feeding rates and survival, and cause oxidative stress, reproductive issues and behavioural abnormalities in many marine organisms [20-22, 25, 27, 28]. Microplastics can also act as vectors for heavy metals, antibiotics and other toxic or dangerous substances, which can lead to further cumulative impacts on organisms [21, 28-33]. Additionally, microplastics can contaminate commercially important species and have been found in marine products sold for human consumption [34-38].

The impacts of microplastic contamination on human health, while of concern, are poorly understood and are still being debated [37, 39-43]. There is some evidence that human microplastics consumption has the potential to lead to inflammation, disruption to immune function, neurotoxicity and some types of cancer, however experiments with human tissues are still rare and largely suggestive [37, 42, 44-46]. Nevertheless, according to the precautionary principle the current lack of evidence should not be a reason for disregarding potential threats or for taking action to prevent the potential threat from occurring. Microplastics are a suite of contaminants, with various properties and sources which enter the environment through multiple pathways which makes their mitigation and management difficult [26]. As such, there is a valid need to improve the management and mitigation of these widespread pollutants.

This paper provides a brief overview of some of the major sources and pathways of microplastics in the marine environment (Section 2). Section 3 examines current policy and strategies employed in the European Union as a benchmark for possible uptake into Australian policy, followed by the examination of more mitigation and management approaches in Section 4. Section 5 looks at some of the major sources and pathways of microplastics in marine environments along with various options available to mitigate and manage their introduction to these environments. The outcomes of the round table workshop are discussed in Section 6. We consider the framework for the development of options to address the management of microplastics in the marine environment in Section 7 and outline suggested areas for policy development in Section 8.

2. MICROPLASTICS – SOURCES

This section summarises sources and pathways of microplastics in the marine environment. This analysis helps us understand the current state of knowledge, and methods used to address the problem as a key to developing future options.

The vast majority of marine microplastics come from terrestrial sources (98 percent) [47]. Microplastics can result from the breakdown of larger plastic items through corrosion, breakage and degradation. They can also be intentionally added to products to perform a variety of functions including binding, film forming and surface coating (e.g. fertilisers), and corrosive effects (e.g. commercial cleaning products and personal care and cosmetics products (PCCPs)) [47-54]. Due to the discrepancy in categories and the lack of clear classification guidelines, this paper applies Browne's [54] approach and classifies microplastics according to their source.

Currently there is a substantial lack of quantitative data on the sources of microplastics in the marine environment. The major sources that are most well quantified include: PCCPs, fibres in synthetic clothing, tyre wear particles, production pellets, fertilisers and biosolids (**Paper 1**) and these will be the focus of further discussion in this paper. Microplastics entry into the marine environment can be via multiple pathways but these are also poorly studied [54-57]. One such pathway - waste water treatment plants - is relatively well understood and will be the focus of discussion in this report [54, 58, 59].

Despite recent efforts to identify the sources and pathways of microplastics into the marine environment, major knowledge gaps exist that limit the management and mitigation of microplastics. Recently, California enacted two bills that focus on quantifying and managing microplastics in marine and aquatic environments [60]. These bills provide evidence of the knowledge gaps and highlight the need for standardised methods for quantifying microplastics in the marine environment [60]. Several recent studies have investigated methods to improve the quantification of microplastics [61-66], however, no widely accepted, standardised sampling and/or analysis method currently exists [60].

Our understanding of the impacts of microplastics on marine organisms and human health is also limited [20, 26, 37, 40] and it is unclear at what concentrations microplastics become a significant environmental and health threat. For instance, "how much is too much?" While many studies have demonstrated negative impacts of microplastics on marine organisms, according to a meta-analysis and a systematic review conducted by Bucci et al. [26], approximately 17 percent of the studies have used concentrations reported in nature, making the results less environmentally relevant.

The need for science-based solutions to the microplastics problem has been widely emphasised [60, 67] and are covered in greater depth later in this options paper. Several countries are reducing their plastic waste through bans on single use plastics [68, 69]. These efforts have mainly focused on macroplastic pollution [60, 70]. According to Herberz et al. [71], bans on all single-use items (not just plastic) would be needed to achieve positive and sustainable environmental outcomes. Single-use plastic bans are only a partial solution, as their impact is limited, as are the impacts of the entrepreneurial clean up approaches aimed at removing plastic from the ocean (e.g. The Ocean Cleanup Project https://theoceancleanup.com/; Seabin Project https://seabinproject.com/; Mr. Trash Wheel https://www.mrtrashwheel.com/; Two Hands Project http://www.twohandsproject.org/; Tangaroa Blue Australian Marine Debris Initiative https://www.tangaroablue.org/). These approaches can be successful, however they are often small scale and focus on macroplastics [72, 73]. The latter also focuses on removing the plastic once it is in the environment and, arguably, having already caused damage. It has been found that innovation in technology alone to remove macroplastics is not enough to significantly reduce marine plastic pollution and these current technologies are unable to remove microplastics [74].

Action is required on microplastics, given their high abundance, environmental availability, global spread and possible negative impacts on marine biota and human health, and absence of effective mitigation options [7, 11-13, 16, 18, 20, 21, 26, 75, 76]. Without devaluing the importance of clean-up activities, this report focuses on preventative measures. These measures are particularly pertinent given predictions of plastic waste entering the ocean are expected to potentially triple in the next 20 to 30 years [5, 8-10, 77], and since COVID-19 and the increase in use of single use plastics these estimates are now seen as conservative [78]. Moreover, the small size and high rate of environmental contamination make removal of microplastics from the marine environment notoriously difficult.

The recent Pew Charitable Trusts report found that current actions and a ‘business as usual’ approach to plastic pollution will result in minimal reductions to plastic waste [77]. It suggests that a greater scale of action is needed on behalf of governments and industry in driving upstream and downstream action; both upstream and downstream solutions need to be deployed simultaneously. The Pew report suggests that it is current inadequate regulatory frameworks, business models and funding mechanisms, not technological solutions, that are preventing the development of solutions to the plastic crisis. As a result there needs to be a substantive shift of investment away from the production and conversion of virgin plastic; the implementation of a new circular economy; different solutions for different regions and priorities; and that changing from a ‘business as usual’ to a ‘systems change scenario’ will have co-benefits for the climate, environment, economy and the UN Sustainable Development Goals [77].

Therefore, this options paper investigates currently available options for microplastic pollution management and mitigation that either have been proposed or implemented around the globe. It also links those options to broader circular economy approaches and provides current knowledge-based advice on which available options are potentially most viable for implementation in Australia.

3. ASSESSMENT OF CURRENT POLICY

3.1 Action by the European Union

The European Union (EU) has the most advanced framework directives and action plan related to microplastics. These have been developed to guide and direct member states responses, consultations and engagement, 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 [79]. There is also a small but significant literature assessing the policy and regulatory issues [for example, 50, 80, 81, 82] related to intentionally added microplastics.

The EU has enacted the European Strategy for Plastics in a Circular Economy (2015), a Directive on Single-Use Plastic, the Eco-design Directive, Waste Framework Directive and various other waste management and prevention strategies. It is seen as a leader because of its plastics pollution policies and enforcement of the ‘polluter pays’ principle which puts responsibility back onto industry.

The European Strategy for Plastics in a Circular Economy (2015) specifically asks for a reduction of the use of ‘oxo-plastics’ and intentionally added microplastics in line with REACH procedures. REACH is a regulation of the EU that protects human health and the environment from the risks posed by chemicals and ensures industry responsibility for these risks. As outlined in the Strategy, a Cross Industry Agreement (CIS) was launched in 2018 and “is a voluntary collaboration for the prevention of microplastic release into the aquatic environment during the washing of synthetic textiles” [83]. Signatories include five European industry associations that represent the global value chain of garments. To date, the signatories of the Agreement have created a dedicated working group to develop standardised test methods “for the determination of release, identification and evaluation of microplastics from textile sources, during manufacturing and use”[84]. They are also investigating the development of a centralised, global database for data gathered by the signatories and stakeholders outside of the Agreement. Their research into technological solutions and use of filters is still in the testing phase [84].

In 2019, the European Commission presented the European Green Deal which is a new growth strategy to make Europe more sustainable. It includes a New Circular Economy Action Plan and targets zero waste pollution. The New Circular Economy Action Plan has a key action to restrict intentionally added microplastics and measures on unintentional release of microplastics by 2021. It builds upon the 2015 Strategy’s actions on microplastics and states:

“In addition to measures to reduce plastic litter, the Commission will address the presence of microplastics in the environment by:

- restricting intentionally added microplastics and tackling pellets taking into account the opinion of the European Chemicals Agency (ECHA);

- developing labelling, standardisation, certification and regulatory measures on unintentional release of microplastics, including measures to increase the capture of microplastics at all relevant stages of products' lifecycle;

- further developing and harmonising methods for measuring unintentionally released microplastics, especially from tyres and textiles, and delivering harmonised data on microplastics concentrations in seawater;

- closing the gaps on scientific knowledge related to the risk and occurrence of microplastics in the environment, drinking water and foods.

Some progress on these actions has been made. In June 2020, the ECHA's Committee for Risk Assessment adopted its opinion on the restrictions on intentional use of microplastics. However, research by Clausen et al. [85] found that significant stakeholders (such as researchers, small and medium enterprises) were not involved in the consultation process [85]. The ECHA's Socio-economic Analysis committee continued the process through a consultation of the draft opinion on the costs and benefits of this proposal [86], and as of September 2020 the opinion making progress is still ongoing [87] (for more on ECHA see below).

Also in June 2020, during the revision of tyre labelling regulation it was agreed by the EU co-legislators to "use delegated acts regarding mileage and abrasion as soon as a suitable method is available and on the basis of a thorough impact assessment," and that "the Commission has been following the work of the stakeholders from the tyre sector on the development of a measurement standard, as well as work on type-approval requirements" [88]. The Commission has also funded research projects that support innovation in the plastics sector [88].

Furthermore, the Commission will address emerging sustainability challenges by developing a policy framework on:

- "sourcing, labelling and use of bio-based plastics, based on assessing where the use of bio-based feedstock results in genuine environmental benefits, going beyond reduction in using fossil resources;

- use of biodegradable or compostable plastics, based on an assessment of the applications where such use can be beneficial to the environment, and of the criteria for such applications. It will aim to ensure that labelling a product as 'biodegradable' or 'compostable' does not mislead consumers to dispose of it in a way that causes plastic littering or pollution due to unsuitable environmental conditions or insufficient time for degradation.

The Commission will ensure the timely implementation of the new Directive on Single Use Plastic Products [29] and fishing gear to address the problem of marine plastic pollution while safeguarding the single market, in particular with regard to:

- harmonised interpretation of the products covered by the Directive;

- labelling of products such as tobacco, beverage cups and wet wipes and ensuring the introduction of tethered caps for bottles to prevent littering;
- developing for the first time rules on measuring recycled content in products." [89]

With regard to textiles, it states:

"In the light of the complexity of the textile value chain, to respond to these challenges the Commission will propose a comprehensive EU Strategy for Textiles, based on input from industry and other stakeholders. The strategy will aim at strengthening industrial competitiveness and innovation in the sector, boosting the EU market for sustainable and circular textiles, including the market for textile reuse, addressing fast fashion and driving new business models. This will be achieved by a comprehensive set of measures, including:

- applying the new sustainable product framework to textiles, including developing eco-design measures to ensure that textile products are fit for circularity, ensuring the uptake of secondary raw materials, tackling the presence of hazardous chemicals, and empowering business and private consumers to choose sustainable textiles and have easy access to re-use and repair services;
- improving the business and regulatory environment for sustainable and circular textiles in the EU, in particular by providing incentives and support to product-as-service models, circular materials and production processes, and increasing transparency through international cooperation;
- providing guidance to achieve high levels of separate collection of textile waste, which Member States have to ensure by 2025;
- boosting the sorting, re-use and recycling of textiles, including through innovation, encouraging industrial applications and regulatory measures such as extended producer responsibility" [89].

The gaps in EU plastic policies/strategies before the Green Deal have been identified as:

- The use of recycled content – at current levels, and even if ambitious targets are followed, they will not provide for a full shift to a circular economy for plastics;
- The inclusion of other plastics in container deposit schemes in addition to beverage bottles;
- Unintentional release of microplastics such as tyre wear (that could be incorporated into existing legislation such as the EU tyre label regulation (EC/1222/2009);
- The introduction of extended producer responsibility schemes for fishing gear [90].

These gaps have been addressed by the European Commission through the new Green Deal where the Commission will consider legal requirements for the increased mandatory use of recycled content [91], unintentional release of tyre wear [92] and including other plastics to be recycled such as batteries and packaging [89]. The extended producer responsibility schemes for fishing gear have been addressed in the 2019 Directive on the Reduction of the Impact of Certain Plastic Products on the Environment. It says “Member States should, in line with the polluter-pays principle, introduce extended producer responsibility for fishing gear and components of fishing gear containing plastic to ensure separate collection of waste fishing gear and to finance environmentally sound waste management of waste fishing gear, in particular recycling” [93]. This Directive does not address microplastics but it does encourage all producers to limit the use of microplastics.

3.2 The European Chemicals Agency (EHCA)

In March 2019, the European Commission requested an Annex XV dossier on intentionally added microplastics to be prepared by the European Chemicals Agency (EHCA). The dossier states “the restriction, if adopted, would cover intentionally added microplastics in products such as cosmetics, detergents, agricultural products, and in paints” [90].

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” [94].

The ECHA’s proposed restriction targets intentionally added microplastics that will inevitably be released into 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 [94].

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 such as synthetic clothing or textiles 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 are 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. Lessons from the EU of particular importance include: that the European Commission and Parliament have a) acknowledged the complexities of plastic pollution; b) led the process through their legal framework; and c) are updating their policies and action plans to reflect the constantly changing data being collected. It is however, too early to assess the effectiveness of the EU policies, but what is worth contemplating is a federally led approach in Australia, similar to the EU, to provide guidance on the way forward for states and industry.

4. CURRENT APPROACHES

4.1 Circular economy approaches

A circular plastics economy approach can reduce plastic pollution, and many regions around the world, including the EU, have started to transform their economic systems. The traditional liner economy follows a model of resource consumption that is based on ‘take, make and dispose’, which is unsustainable. The circular economy system is designed to reduce, reuse, repurpose and recycle [95]. In principle, it should retain resources within the economy, minimising resource depletion and waste [96]. The movement to a circular economy requires changes in not just manufacturing and packaging, but also significant modifications in design and materials [97]. Innovation in technology and economic modelling is needed to move from a linear economic system [98]. To achieve real change through a circular economy, the entire stewardship chain including plastic producers, distributors, consumers and other actors involved in the lifecycle of a product need to be engaged and involved in the process. For example, to reduce microplastic releases from synthetic textiles the actors involved in the circular economy process would include, amongst others, the designer of the textile fibres, the textile product designer, the washing machine designers, water infrastructure engineers and consumers [47, 67].

Recent studies have shown that continuing with ‘business as usual’ scenarios utilising linear economy approaches will not reduce current rates of plastic pollution. However, alternative scenarios demonstrate that that the introduction of circular economy systems will reduce plastic pollution by up to 80 percent, including a 2 million ton reduction of microplastics entering the environment by 2040 [77, 99]. In addition to the circular economy approaches, for the alternative scenarios to work effectively, plastic consumption needs to be decreased and plastic alternatives more frequently used [77]. Recently, KPMG was commissioned by the CSIRO to investigate the economic pay-off for a circular economy. Their report found that while the transition to a circular economy across all industry and all aspects of the economy is ambitious, the benefits of its implementation are estimated to contribute $210 billion in GDP and 17,000 full time equivalent jobs in Australia by 2048 [100].

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. In response, the Australian Government released a series of high level commitments and the 2019 National Waste Policy Action Plan [101]. The action plan presented targets, actions and timeframes to deliver these actions. It has been argued, however, that the framework in the National Waste Policy is too focussed on recycling and will therefore not deliver a truly ‘circular’ system [102] including extended producer responsibility, product design and reuse. The EU’s Action Plan on a Circular Economy, similarly, focusses mostly on recycling [103].

Australian state, territory and local governments are also pursuing circular economy approaches after endorsing the National Waste Policy [see for example, 104, 105-107]. For example, in Tasmania, there are numerous stakeholders discussing the transition to a circular economy [104]. The Tasmanian government released a Draft Waste Action Plan for consultation in 2019. The Draft Plan lays out the steps towards a circular economy through actions such as introducing a waste levy, container refund schemes and achieving 40 percent recovery rate from all waste streams by 2025 and 80 percent by 2030 [105]. Microplastics are not addressed. The Victorian government's Recycling Victoria Plan states that it is a circular economy policy and recycling plan that will "fundamentally overhaul our recycling system" [106]. While it does address the 'reuse' and 'reduce' parts of a circular economy it is mostly focussed on recycling. Similarly, to the Tasmanian draft plan, it does not address microplastics. However, state-based approaches consider the impact on local governments and businesses that will be most affected by the transition to a circular economy.

4.2 Product Stewardship

Product stewardship links to elements of a broad sustainability agenda: traceability and validation, with a key element the management of recycling processes, including audit compliance and inspection systems. Product stewardship sees a producer's responsibility for a product extended into the post-consumer stage of the products life cycle [108]. It focuses on closing the product life cycle by making producers responsible for their products from the cradle to the grave. In particular, the producers themselves are in charge of recycling or (at least) disposal in an environmentally sound way [109].

Conceptually, product stewardship involves two core components: responsibility and regulation (Lewis 2005), recognizing that both include a range of perspectives, from legally mandated processes to voluntary codes of conduct and behaviours. Product stewardship "has become one of the core principles behind the policy framework for packaging in Australia—the National Packaging Covenant (NPC)" [110] and has been formalised through the *Product Stewardship Act 2011*.

The *Product Stewardship Act 2011* provides a legislative framework to support initiatives related to manage microplastics and to support existing industry-led initiatives and consumer and/or societal concerns. The *Product Stewardship Act 2011* was recently reviewed and the final report on the review was tabled on 8 July 2020 [111]. The Product Stewardship Act (with amendments incorporating the Government's response to the review) is being incorporated into the *Recycling and Waste Reduction Bill 2020* to provide a national framework to manage waste and recycling across Australia [112]. As at 10 November 2020 the bill was still being debated in parliament.

Product stewardship can be the basis of strong policy development, but Tasaki et al. [108] notes, "different stakeholders have varying perceptions of the concept and role of producers … Policy disputes … are often fuelled and confused by these different perceptions, and assignment of responsibility has typically been an issue of focus in such disputes" [108]; that is, the level of 'responsibility' held by producers *vis. a vis*. consumers over the use and disposal of products.

Industry engagement in product stewardship is a critical element, but a key aspect is to ensure a workable national basis to initiatives to avoid fragmentation and multiple and/or competing arrangements for products that are marketed nationally.

4.3 Extended producer responsibility

Extended Producer Responsibility (EPR) is a type of product stewardship and is a critical component of a circular economy. Through EPR, producers are legally and financially responsible for all aspects of their products' impacts on the environment. The Organisation for Economic Cooperation and Development (OECD) define EPR as an 'environmental policy approach', that is characterised by:

"1. The shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities; and

2. The provision of incentives to producers to take into account environmental considerations when designing their products" [113].

This approach is of particular significance and will contribute to the reduction of microplastics in the environment [see 114, 115, 116]. According to Hamilton et al. [117] "when combined with zero-waste communities and bans on new infrastructure…extended producer responsibility can ensure that producers of plastic products and fast-moving consumer goods avoid unnecessary plastic production, design products for long and repeated use, and invest in the systemic changes required to make a circular economy succeed."

EPR can be voluntary and driven by corporate social responsibility policies, but it is usually managed through legislation [118, 119]. Many regions have implemented EPR policies including the EU (and individual countries within the EU), Canada and the USA [120]. A number of current initiatives have been constrained by the effects of the COVID-19 pandemic limiting legislative action. Container deposit schemes are one example of an EPR policy and they are operational across a number of Australian states and territories. However, for EPR programs to be effectively implemented they need robust recycling technologies and commitment from producers and governments to implement the systematic changes required.

A study by Deloitte commissioned by the European Federation of National Associations of Water Services (EurEau) argued that consumers should not have the burden of the costs of microplastic pollution [121]. The report finds that the precautionary principle can be applied through EPR under the EU's Water Framework Directive. While the principle is not yet being applied in practice, should it be enforced, polluting producers will be made to bear the costs of removing microplastics from water [121]. If this eventuates it will set a precedent for EPR and industry responsibilities for microplastic pollution.

4.4 Consumer Behaviour

Technological developments are essential to creating a circular economy for plastics, but so is a shift in consumer and producer behaviour. This shift in behaviour can be steered by the consumers themselves and/or by governments, non-governmental organisations (NGOs) and industry. According to a report by the Secretariat of the Convention on Biological Diversity (CBD) and the Scientific and Technical Advisory Panel [122] "many companies now see packaging and plastics sustainability as part of broader corporate social responsibility, and negative brand image is becoming a major driving force, which is being harnessed in the interests of improving packaging materials and technologies."

Consumer behaviour and public opinion has been swayed by legislative changes, NGOs, and through the influence of the media [123, 124]. Consumer driven demand has had a positive impact on industry behaviour, especially in the reduction of microbeads. In Australia, changes have been industry driven and major retailers such as Coles and Woolworths have voluntarily introduced microbead bans [125]. Multinational companies such as Johnson and Johnson, and Proctor & Gamble agreed to gradually remove polyethylene microbeads from their products in 2015 due to public pressure [126]. However, numerous cosmetic companies are continuing to add microplastic additives into their products as they do not fall under the definition of a microbead. There are also cosmetic products that contain 'sceptical' microplastics, which are synthetic polymers for which there is not enough information available to assess their impact on human and environmental health (see https://www.beatthemicrobead.org/) [127, 128].

Psychologists have found that there is a bias towards the exclusivity and authenticity of products or 'essentialism' which undermines the principles of a circular economy [129]. However, recent research suggests that this bias is changing, and consumers value and are willing to pay for products which have been reused as part of the circular economy [130-132]. Socio-economic status and culture/norms can also influence consumer decision making [133]. For instance, consumers in developing countries buy a larger portion (68 percent) of synthetic textiles than in developed countries [47]. Consumers in general are less informed about microplastics such as tyre wear, synthetic textiles and fertiliser than they are about microbeads [124].

A recent study of public understandings of microplastics in the UK found that most of the participants were unaware of microplastics, although many had heard about microbeads through the changes to national legislation through the media. Plastic pollution was seen by participants as being a macro level issue (i.e. the Pacific Garbage Patch) and there was little understanding of the science behind microplastic pollution. Moreover, media influence and cultural perceptions of plastic influenced their understanding of the microplastic pollution problem [124]. For consumers to drive change on microplastics they need to have informed knowledge and awareness about the microplastics problem, but also the motivation and skills to steer change (why should I do something about this and how?) [134].

Education, public outreach programs and citizen science initiatives are useful for increasing people's knowledge and modifying their behaviour with regards to plastics and microplastics

[123, 135]. ‘Nudging’ has been used by decision makers in policy design. Nudging occurs where decisions are based on behavioural insights to steer people’s behaviour in a certain direction. Nudges have been used to change consumer’s attitudes to bottled water [136] and single use plastic bags [137]. They can also be a potential solution to changing behaviour around microplastic pollution, as seen in consumer support for industry action to reduce microbeads in personal care products.

More research is needed to understand consumer behaviour, in particular as a result of COVID-19 where single plastic use has increased and will inevitably increase microplastic pollution [78]. This future research will be of benefit to decision makers in establishing a circular economy and policies to reduce microplastic pollution.

4.5 Regulatory options

The problem of regulatory ‘fit’ – simply ensuring alignment between the regulatory instrument and the purpose and task to which the instrument is directed has been a common concern for decades. The lack of fit and its consequences was clearly presented by Maslow in his comment “I suppose it is tempting, … when all you have is a hammer, [to make] everything look like a nail” [138]. Developing appropriate regulatory options are important. Matching the correct tool to the problem that has been identified is necessary.

While legislation is a key tool, Maslow’s aphorism reminds us that limiting the choice of tool may result in suboptimal outcomes. In exploring regulatory options, we are keen to include the broadest possible interpretation of regulation being used. We recognise that a range of tools are available. These include industry or consumer driven codes of practice or hybrid approaches or instruments [139] that link legislation to market or industry/community motivations and actions. It is also important to focus on sector relevant tools (Table 1) and to look at workable options, that are effective, efficient, and economic.

5. MICROPLASTICS – SOURCES, PATHWAYS AND OPTIONS

The following sections examine microplastics that originate from a variety of sources. Each source is discussed in the context of why it is a potential problem along with the options available to mitigate the discussed source. A review of policy options is undertaken, and information gaps identified for further discussion.

5.1 Microbeads in Personal Care and Cosmetic products and cleaning products

5.1.1 Problem

For the past 40 years, small plastic particles have been used in a large variety of personal care and cosmetic products (PCCPs), including facial and body scrubs, body cleansers, shower gels, foundation and mascara. Microplastics have been used as a replacement for natural products (e.g. pumice, seeds, oatmeal) for their gentle abrasive qualities, low cost, appearance and ease of manufacturing [140-143]. Multiple studies have investigated the qualities and quantities of microplastic particles in PCCPs around the world. Many of these particles are referred to as microbeads, however synthetic fibres and other types of microplastics can also be found in PCCPs [48, 144]. Microbeads have been reported to vary in size, from about 4μm to over 1200μm [48, 141, 145-147]. Microplastics are also added to a large variety of industrial and domestic cleaning products, including blasting medias [140, 148-150]. Unfortunately, there are no reliable estimates of the contribution of microplastics from industrial and domestic cleaning products to the marine environment at this time [54], and these sources are not considered further in this section, although it is identified as a gap for future research.

In a recent review of the literature conducted by Guerranti et al. [48] it was reported that microbead concentrations in some PCCPs can be over 50,000 particles per gram of product. As these products do eventually get washed off, they have a high potential of entering the environment. In fact, up to 39 tons of microplastics from shower gels have been estimated to enter the environment each year in China [145]. When combined with other PCCPs sources this estimate grows to over 300 tonnes per year from China alone [147]. This number is lower than estimates (approx. 500 tonnes/year) of microplastic released from five primary PCCPs groups in Germany. For all of the European Union, including Norway and Switzerland, it was estimated that 4360 tons of microbeads were released from PCCPs in 2012 [151]. However, several countries have banned microbeads in rinse-off PCCPs since the 2012 international “Beat the Microbead” campaign [48, 127, 128] or encouraged voluntary phase-outs [48, 152, 153]. Therefore, volumes released into the environment are likely to have decreased, however targeted research is needed to provide quantitative evidence of such a decrease.

It is important to note that existing bans and phase-outs generally only apply to rinse-off cosmetic products [48, 153] as it has been argued that wipe-off products are less likely to enter the environment [153], however there is little evidence to support this. Additionally, the issue of microplastics in leave-on PCCPs has not been effectively addressed on a global scale, despite being potentially a greater contributor of microplastics in the aquatic environment than rinse-off PCCPs [154]. This has led to Guerranti et al. [48] advocating for global bans on microplastics in PCCPs. Additionally, many countries have not undertaken any action and therefore the potential of microplastic pollution from PCCPs remains high [128, 144].

5.1.2 Options

A review of the literature identified a number of options to address microplastics from PCCPs. These are illustrated in Figure 1 and described below:

Legislation

- Bans on use of microbeads and other microplastics in a larger range of PCCPs [48].

Incentives: Social and Commercial

- Industry responding to community concern with substitutes or replacements.
- Social and commercial incentives for manufacturers to use natural products (such as nuts, shells etc.) to replace microplastics in their PCCPs. Several companies have already taken the initiative, but others have replaced microbeads with other plastics [48, 54, 128].
- Investigation and incentives into the use of natural alternatives for commercial cleaning products and blasting media.

Public Awareness and Education

- Increasing public awareness of microplastics in PCCPs through clear labelling of products to allow for informed decision making when purchasing products. Anderson et al. [155] investigated the level of public awareness about microbeads in PCCPs and reported that several participants were not aware or did not consider ingredients in the products they used. This study highlighted a need for clear labelling, which may help with public awareness and consequently decision making when purchasing.

Technology and Innovation

- Closed circuit sandblasting systems (e.g. Pinovo: http://www.pinovo.com) have been shown to largely eliminate microplastics particle loss into the marine environment during cleaning of industrial steal surfaces [156].
- Further research is required to investigate technologies that may allow reduction in microplastics used in PCCPs and technologies that allow capture of the microplastics lost during the use of PCCPs. Some of these are discussed further on.

In general, there are knowledge gaps in this area, particularly in an Australian context, and further research is required to identify all viable options.

5.2 Microfibres in synthetic clothing

5.2.1 Problem

Polyester, polypropylenes, polyamides and acrylics have been commonly used in synthetic textiles [144, 157, 158], which expel substantial quantities of microfibres during domestic and commercial washing [7, 49, 67, 144, 159]. Multiple studies have investigated the proportion of microfibres released during washing with estimates ranging from 1900 microfibres being release per wash of a single garment [7] to as many as over 17 million fibres being lost in a typical five kilogram wash of polyester fabric [49, 159]. While the loss of microfibres from synthetic clothing during washing has been shown to decrease with multiple washes [49, 160], it is never eliminated. Several studies have also investigated whether different detergents and softeners can reduce the loss of fibres from synthetic textiles, however the results were highly variable and contradictory [49, 158-160] offering no suitable management solution. Many washing machine filters have not been specifically designed to retain these particles, and due to the microfibres' small size (~11.9 μm diameter, 5 mm length [49, 161]) the majority of wastewater treatment plants also fail to capture them [58, 67, 159, 162], thus they are released directly into the environment.

Microfibre loss can occur during the use and wear of synthetic textiles, however quantitative evidence available at this time is very limited [54]. A recent study from the Institute for Polymers, Composites and Biomaterials of the National Research Council of Italy and the University of Plymouth has suggested that the loss of the microfibres from synthetic textiles during wear may be as significant as the loss during washing [163].

Microfibres are one of the most common types of microplastic pollutants found in the marine environment [7, 164, 165]. Microfibres have been found to be more toxic than other forms of microplastics in numerous studies [144, 166-168]. Due to their very small size (0.25mm) [165], they are more available for absorption and consumption by smaller organisms from lower trophic levels. Indeed, 70 percent of microplastics ingested by zooplankton in the northern South China sea have been reported to be microfibres [169]. An extensive review of microplastic effects across all levels of biological organisation has identified size as one of the major factors of whether the effect was detected or not, stating that effects were more commonly observed with the particles of smaller size [26]. This highlights the potential for microfibres to be of greater detriment to the environment than other forms of microplastics. A further cause for concern are the recent investigations that have highlighted the potential serious negative impacts of microfibres, and the chemicals associated with them on human health. This includes the potential increase in likelihood of some cancers and possible damage to vital organs (e.g. stomach, liver, lungs) [42, 43].

Measures to mitigate and manage microfibre pollution are of great importance given the role synthetic textiles play in our everyday life. Yet despite the demonstrated impacts of microfibres, limited action is being taken to reduce their release into the environment [7, 26, 144, 165]. Significant knowledge gaps in understanding sources and pathways of microfibres in the marine environment greatly limit the mitigation and management strategies available, and hence support of research initiatives in this area should be a priority [54, 67, 144].

5.2.2 Options

A review of the literature identified a number of options to address microfibres from textiles. These are illustrated in Figure 1 and described below:

Legislation

- In February 2020, France enacted a law mandating the provision of microfibre filters on all domestic washing machines by 25 December 2025, with incentives for manufacturers if they include such filters prior to this date.

- A significant portion of clothing used in Australia is manufactured overseas, therefore international collaboration in the product stewardship area and regulations on the quality of imported products should be investigated.

Incentives: Social and Commercial

- Develop incentives to encourage industry to employ product stewardship approaches and encourage reduction in the use of synthetics in their products, increase in the use of technologies that would reduce loss of microfibres, and technologies (e.g. washing machine filters) that would allow capture of microifbres lost during washing cycles.
- Develop incentives to encourage consumer responses with respect to using technologies that could allow capture of microfibres during washing cycles (e.g. filters), purchase of products that implement technologies and product stewardship approaches that allow reduction in microfibre loss from their products.

Public Awareness and Education

- Improve public awareness of the issue. Currently, there is limited quantitative data on the level of public awareness of microfibre pollution issues in general, and for Australia specifically, with some studies that have investigated these questions being limited by small sample sizes and/or being regionally restricted [170, 171]. A UK based study of 71 young female consumers investigated garment disposal habits and purchasing attitudes. This study identified a general low level of understanding of the impact of consumer behaviour on the environment. They also demonstrated that there was a limited understanding of textile production process and its impacts [172]. A Poland based study conducted 288 surveys designed to identify consumer's 'environmental commitment and behaviour' patterns and found that the aesthetic, financial and functional benefits of a clothing item generally outweighed their sustainability rating when making purchasing decisions [173]. Despite these limitations, some manufacturers in Australia have already taken the initiative by advertising their products as synthetic free. Further research is required to understand Australian consumer knowledge of microfibre impacts on the environment and their attitude towards sustainable and circular fashion approaches to advise on the best future actions in terms of management and mitigation of microfibre impacts.

Technology and Innovation

- Develop and implement modifications during the production and finishing process, and material designs [49, 54]. Hernandez et al. [158] have suggested that fibre staple length can influence the amount of fibres being released, with shorter/smaller fibres being more likely to be lost during the washing process. These observations suggest that changing the fibre length could reduce microfibre release from domestic washing. Félix-de-Castro et al. [157] made a similar suggestion, proposing the use of continuous fibres during textile production processes. Moreover, as the majority of microfibres are lost from the edges (averaging at 84 percent), cutting methods can have a substantial effect on the amount of microfibres being released during washing [174, 175]. Scissor-cut textiles have been shown to release up to 31 times the amount of microfibres compared to laser-cut [174, 175]. When it comes to yarns, rotor yarns have been demonstrated to release higher quantities of microfibres than other types of yarn[175]. Processed surface textiles (e.g. fleece) have also been shown to lose significantly larger amounts of microfibres than non-processed surface textiles [174, 175]. Finally, recent studies have demonstrated that microfibre loss during wear, as well as laundering was lower for the materials that were made from continuous filaments and had a more compact woven structure than twisted yarns [163]. These findings suggest that material design considerations during the manufacturing process may substantially reduce microfibre release during wear and washing and, hence, reduce microfibre environmental contamination.
- Mechanical processes, such as calendaring, and chemical coatings, that can reduce microfibre loss, have also been investigated, however the data is still limited [157]. Recent innovative research has demonstrated that coatings from biodegradable polymers can reduce the loss of microfibres from treated fabric without affecting a range of fabric properties [176]. De Falco et al. [177] has also reported that the amount of microfibres lost from polyamide fabric can be reduced by 90 percent when a novel pectin treatment is applied [177]. Further research in the effectiveness of various biodegradable and non-toxic coatings is needed to develop economical and environmentally sound manufacturing strategies.
- Recently a range of products (Cora Balls, Guppy Friend bags, Lint LUV-R filter) have been developed that can be used during washing and may capture some of the lost microfibres, however the efficiency of different options in removing microfibres varies greatly (between18-87 percent) [43]. A recent comparative study of the Lint LUV-R filter and the Cora Ball has reported that while both options reduced microfibres in the effluent during washing of fleece blankets, the Lint LUV-R filter captured substantially higher percentage (87 percent) of microfibres by weight. The authors also reported that the Lint LUV-R filter reduced the total weight and length of the fibres in the effluent [178].

However, Browne et al. [67] argues that the data is still insufficient to reliably assess the effectiveness of these products.

- More effective washing machine filters are another viable option and different designs are in development. It is hoped that these filters will capture microfibres from water expelled from washing machines before entering the drain [54, 179]. Browne et al. [67] in a replicated study demonstrated that some filters can reduce microfibre content in the effluent from domestic washing by up to 74 percent. However, this study was one of the first replicated studies of its kind, with the authors highlighting the need for further research in this area [67].

In general, there are significant knowledge gaps in this area, particularly in an Australian context, and further research is required to identify all viable options.

5.3 Tyre wear

5.3.1 Problem

According to the Pew report, tyre wear is the largest source of microplastic leakage, contributing to 78 percent of microplastics leakage by mass [77]. Modern tyres consist of several components, including synthetic fibres (such as butadiene and its derivatives), which are plastic polymers [47, 180, 181]. Microplastics are released into the environment through the wear and tear of tyres. The exact amount of microplastics released from tyres during driving depends on several factors, such as tyre composition and size, weight and type of vehicle, speed and driving behaviour, road surface and weather [47, 182, 183]. Some studies have estimated that urban driving can lead to the largest tyre wear particles emissions, followed by highway driving. Lorries, trucks and busses have been estimated to emit at least three times greater amounts of tyre wear particles (mg/vkm) than that of passenger cars [183, 184]. However, a Norwegian study indicated that as passenger cars generally tend to cover greater distances per year, they are responsible for greater total losses [183]. It is likely that further studies would highlight differences between countries.

While less than 20 percent of tyre wear particles have been estimated to enter aquatic environments [185], they contribute 10-28 percent to the total marine microplastic pollution [47, 182, 186]. Tyre wear particles are the second most abundant type of microplastics (17.1 percent) observed in the tributaries of the Charleston Harbor Estuary, South Carolina, USA [187]. Rivers are thought to be a major pathway of tyre wear particles to the marine environment, with estimates of 1.2 kilotonnes being transported to the Atlantic Ocean per year [188]. Tyre wear particles may also enter the marine environment via road and stormwater run-off, wind pathways, and wastewater treatment plants [47, 189]. However, limited data is available on the exact contribution of each pathway to marine pollution and on the specific effects of tyre wear particles on marine organisms [182, 185, 189]. As there is no alternative to tyres, mitigation strategies have been strongly advocated for, however, most of these options are in the developmental stage [154, 186, 190].

5.3.2 Options

A review of the literature identified a number of options to address microplastics from tyres. These are illustrated in Figure 1 and described below:

Legislation

- Hann et al. [154] has suggested the development of Tyre Approval Regulations that ban tyres with the highest abrasion rates. This is a relatively cost-effective strategy, with the cost of tyres in the United Kingdom estimated to rise by up to £1.43 per unit. Hann et al. [154] highlighted that this measure could reduce emissions to surface waters by 33 percent. Despite this reduction estimate being substantial and other authors also discussing the need for improved tyre quality, there is an issue of other tyre properties potentially being negatively affected with the improvements in tyre wear properties, such as, slip resistance [186].
- da Cunha Rodovalho and de Tomi [191] have proposed improved management of mining tyres. Mining operations use a substantial number of tyres that contribute to global waste tyre rubber, as well as being one of the primary costs of these operations [191, 192]. Tyre consumption rates have been shown to differ between wet and dry seasons, with the dry season having lower consumption rates [193]. Several other factors can also influence the rate of tyre wear, such as truck speed, cornering speed, braking patterns and road surface [191, 193]. da Cunha Rodovalho and de Tomi [191] have proposed to use tonnes kilometre per hour variable as a measure of tyre efficiency, together with other haulage variables in the quarterly mining plans. They have demonstrated that this innovative management approach can maximise productivity of tyres and reduce tyre wear emissions.

Incentives: Social and Commercial

- Develop incentives to encourage industry and consumer responses with respect to tyre management.

Public Awareness and Education

- Will increase as problem of tyre dust becomes more widely understood.
- Including eco-driving component into driver training focusing on driving behaviours that can reduce tyre wear.

Technology and Innovation

- Recycling of tyre particles in the concrete, asphalts and other construction materials have been proposed, with improved material qualities being demonstrated [194]. Similarly, tyre particles have been recycled worldwide for the children playground surfaces [195, 196]. However, tyre particles used in these products may be contaminated with a range of heavy metals and other toxic substances, that may have negative impacts on human health and health of other living organisms [196-198]. The data on "end-of-life" of these recycled products and the impacts on human health and the environment when these products are used and/or deteriorate is limited and requires further investigation [194-198].

- Kole et al. [186] suggested that tyre wear particle emissions could be 20 percent higher from the use of electric cars due to the higher weight of these vehicles, partially compromising the benefits of these technology. They have advocated for a reduction in the battery weight, which would lead to an increase in the net benefit for human health and environment of this technology [186].
- Similarly, the same authors suggested that self-driving cars may help in reducing tyre wear particle emissions, through programming that would allow slower speed on the corners, gentler accelerations and reduced breaking [186], however it is unlikely that we will see this technology in wider use in the near future.
- Changing road surface characteristics is another option for reducing tyre abrasion [183, 186]. Open asphalt concrete has been advocated for this purpose because it is considered to reduce tyre abrasion rates. More work on quantifying these abrasion rates and impacts is needed [186].
- New tyre designs that are more abrasion resistant is an important area of research and may provide further management and mitigation options to reduce microplastic emissions from tyres. Such innovations in tyre design would not only contribute to improved environmental suitability, but also may lead to improved cost effectiveness due to tyre durability and fuel efficiency, as well as safety due to improved grip (https://friendsoftheearth.uk/plastics/tyres-and-microplastics-time-reinvent-wheel) [186]. However, understanding how changes to tyre design may affect safety performance has to be addressed before implementing newly developed technologies.

As mentioned, it is unclear how tyre wear particles enter the aquatic environment. As such, it is harder to estimate the impacts and costs of implementing downstream measures [154]. However, several possible options are outlined below and included in Figure 1:

- Road engineering solutions that allow for the settling of particle-associated pollutants using wet ponds, for example. These have been commonly used in Norway, Sweden and Denmark [183]. Despite some maintenance issues and uncertainty around dimensions and expected treatment effects, these engineering solutions have proven to be affordable and relatively effective in protecting waterways from road pollution [183].
- "Rain gardens" which are a similar concept to "wet ponds" are a water sensitive urban design technique which has been used by some individual councils in Australia (e.g. Woollahra Municipal Council, NSW: https://www.woollahra.nsw.gov.au/environment/water_and_coast/our_projects)
- Sorption of dissolved pollutants through infiltration has also been used in Europe, with variable success. It has been estimated that the inclusion of an infiltration basin as a second treatment to a standard wet pond can increase construction cost by 50 percent,

with maintenance costs ranging between £0.1-0.3 per m^2 of infiltration basin area and 0.1 per m^2 of treated area for soakaways [183].

- Improved management of road water runoff and the use of roadside gully pots may be a viable option for urban areas [183]. The retention efficiency of gully pots can vary but has been reported to be as high as 50 percent [199, 200]. However, the use of gully pots does require frequent and continuous maintenance [183], which would increase the cost.
- In Australia, options similar to gully pots, have been implemented by some individual councils (e.g. Gross pollutant traps and litter nets by the Woollahra Municipal Council, NSW: https://www.woollahra.nsw.gov.au/environment/water_and_coast/our_projects).
- Water Sensitive Urban Design (WSUD) drainage systems have been designed and implemented around the globe. Their effectiveness ranges between 50 to 80 percent. Vogelsang et al. [183] give base cost estimates for some of these systems for use in Europe. The capital cost estimate ranged between £2 -15 per m^2 filter strip area, while operating costs were estimated to be £0.10 per m^2 of filter surface area [183].
- Compact technical treatment units can be an option in areas where infiltration and other alternatives are not possible. Depending on the design, these systems have been shown to effectively remove particles of variable sizes (>50 percent; 45-240μm). A large variety of types and designs have been developed around the world, including Scandinavia, UK and USA. Some of these systems have been suggested to have similar removal rates as wet ponds (up to 80 percent of the total suspended solids) [183]. However, the effectiveness of these systems and cost varies among designs and deployment sites and would require a systematic review to provide more detailed information.

5.4 Fertilisers and Biosolids

5.4.1 Problem

Biosolids are a product of the wastewater treatment process, and result when sewage sludge undergoes strictly regulated treatment. Biosolids are then frequently used as a fertiliser in agriculture all over the world [201-203]. Despite a vigorous treatment process by the wastewater treatment plants, a proportion of the microplastics does get retained in the biosolids [201, 204, 205]. It has been estimated that approximately 0.5-3 percent of biosolids (by weight) are microplastics [201]. In Australia, this number equates to 2,800 – 19,000 tons of microplastics being applied to the Australian agricultural system through the application of biosolids [206]. While this estimate is smaller than that for the USA (44,000-300,000 tons) or the EU (63,000 – 430,000 tones), it is still substantial [206].

Degradation of microplastics in soils raises concerns of heavy metal absorption by microplastics, breakdown of microplastics into nano-plastics and consequential absorption of contaminated nano-plastics by plants [201]. Microplastic accumulation in the soils of agricultural fields resulting from repeated biosolid applications has been demonstrated in several studies with microfibre concentration being particularly high [207, 208]. Furthermore, a Canadian-based research study investigated the transport of microplastics from biosolids and estimated that more than 99 percent of microplastics applied to land from biosolids may eventually be transported to the aquatic environment [208].

Another source of microplastics is through the application of polymer-coated slow controlled compound release particles, termed nutrient prills, which are commonly used for the controlled release of fertilisers, biocides and herbicides [50-53]. However, no information is currently available on whether these particles contribute to soil microplastic contamination and, consequently, to the contamination of the aquatic environment through rain water runoff and alternative pathways [50].

Management of microplastic contamination in biosolids is closely linked to wastewater and sewerage treatment management options, which are discussed in the next section. However, some brief mitigation options are also proposed below.

5.4.2 Options

A review of the literature identified a number of options to address microplastics from biosolids. These are illustrated in Figure 1 and described below. Given the lack of knowledge around the release of microplastics from fertilizers, herbicides, and pesticides it is not possible to provide options at this time.

Legislation

- As with most other microplastic sources, implementation of strict regulations on the amount of micro- and nanoplastics in biosolids that are applied to land could reduce microplastic environmental contamination.
- Stricter control of the import products, that prohibits products containing per- and poly-fluoroalkyl substances (PFSA/PFOS).

Incentives: Social and Commercial

- Further data is required on the effectiveness of these approaches in Australian context.

Public awareness and Education

- Public awareness programmes that focus on appropriate disposal and recycling options may reduce contamination upstream.

Technology and Innovation

- Biosolids contamination by microplastics is linked to the WWTP ability to remove these particles and therefore options listed for WWTP are relevant to biosolids as well.
- Other measures, such as limiting the use of biosolids in agriculture and instead recycling biosolids for products such as fire brick production has been proposed [201]. This study estimated that the use of biosolids would reduce brick firing energy by more than 12 percent [201].

5.5 Preproduction Pellets

5.5.1 Problem

The majority of plastics start their life cycle in the form of pre-production plastic pellets, that usually range in size between 2-5 mm in diameter. Plastic pellets have been identified as one of the main sources of the primary microplastics in the marine environment [8, 47]. They predominantly come from commercial activities and are not usually associated with the general public. Plastic pellets are the source that has the largest consumption estimated to sit at approximately 257,000 ktons per year, followed far behind by textiles at 42,534 ktons per year [47].

Loss of plastic pellets occurs mainly during production, transport or recycling stages and they can enter the marine environment via multiple pathways (e.g. WWTPs, road run off) [47, 209, 210]. Lechner et al. [211] has reported that plastic debris in the Austrian river Danube predominantly consisted of plastic pellets and other industrial raw materials (79 percent) and that microplastic abundance was greater than the abundance of fish larvae. Like many plastic particles, plastic pellets found in the marine environment have been shown to absorb and contain trace metals, in some cases in larger concentrations than local sediments [212]. They have also been shown to be consumed by marine animals, for example sea anemones [213]. This study demonstrated that while concentrations of several elements (e.g. zinc, arsenic, copper etc.) did not differ between control anemones and anemones that were fed plastic pellets, concentration of lead (Pb) was significantly higher in the experimental group [213]. These findings raise concerns about plastic pellet bioavailability and their ability to contaminate marine animals with toxic chemicals.

Despite these findings and high consumption rates of plastic pellets our understanding of the levels of microplastic pollution attributed to this source is limited. There are substantial discrepancies in current estimates, with some reports suggesting that this source accounts for only 0.3 percent of the global release of microplastics to the marine environment [47] and others putting that estimate at 18 percent [8].

“Operation Clean Sweep®” has been developed in the USA by The Society of the Plastics Industry and American Chemistry Council to train employees in plastic pellets spill preventions and raise industry awareness of their responsibility and the impacts plastic pollution can have on the environment [214]. Operation Clean Sweep® is now active in Europe and has been established in Australia through funding from the Victorian state government and support from the Plastics Industry Association and Tangaroa Blue.

It has been suggested that implementation of best practices that is controlled by regulation can cut plastic loss from pre-production pellets almost in half [8]. However, we did not investigate further options on mitigation and management of this source.

5.5.2 Options

Legislation

- Link to Product Stewardship Act 2011 or successor legislation.

Incentives: Social and Commercial

- Operation Clean Sweep® indicates the potential for positive action.

Public awareness and Education

- Increase knowledge and training of staff that manufacture and transport pellets to help reduce accidental spills.
- Organisations such as Tangaroa Blue Foundation are involved in data collection (Australian Marine Debris Database) that informs marine debris mitigation (https://www.tangaroablue.org/).

Technology and Innovation

- Industry development and innovation directed to reduce loss of pellets.

5.6 Wastewater/sewage

5.6.1 Problem

Wastewater is one of the primary pathways of microplastic pollution, rather than a source *per se*. The release of microplastics into the marine environment through wastewater treatment plants (WWTPs) is one of the most studied pathways for microplastic pollution [47, 48, 54, 58]. While modern WWTPs with primary and secondary treatment processes have been estimated to remove up to 66 percent of microplastics, tertiary treatment can increase this removal to 98 percent. Despite this high efficiency, due to the large quantities of microplastics involved, WWTP have the potential to release large amounts of microplastics to marine environment, simply as a function of volumes of water being treated and levels of microplastic contamination [58, 59, 215]. Murphy et al. [58] calculated that about 65 million microplastic particles per day enter the environment in Glasgow from a single WWTP. While a WWTP in Le Havre harbor, France, that receives the effluent of 20 municipalities, was estimated to release 227 million microplastic particles on a daily basis [216]. In the USA, Rochman et al. [127] estimated that 8 billion microbeads per day were released into the aquatic environment via WWTPs. Globally, it was calculated that WWTPs are responsible for approximately 37 percent of all microplastics in the ocean [47], making it one of the primary pathways, seconded only by road runoff [47, 144].

5.6.2 Options

A review of the literature identified a number of options to address microplastics from WWTP. These are illustrated in Figure 1 and described below:

Legislation

- Upgrade all WWTP to tertiary systems as part of ongoing infrastructure programs. More data is required, including cost-benefit analysis to understand the efficiency of effectiveness of such upgrades in the Australian context.

Incentives: Social and Commercial

- Further research is required to understand the effectiveness of such approaches.

Public awareness and Education

- WWTPs are one of the primary pathways of microplastic pollution, rather than a source. Public awareness and education options aimed to reduce microplastic pollution, as discussed with respect to other several sources can be applied to upstream WWTP pathways. Increasing awareness of how to reduce level of microplastics upstream (e.g. fibres from synthetic textiles during washing cycles, from PCCPs, or litter) to minimise the level of microplastics that enter WWTPs may be an effective solution.

Technology and Innovation

- Sand and anthracite coal filtration and chlorinate disinfection have the lowest capacity to remove microplastics (15-17 percent). Activated sludge has been shown to remove up to 67 percent of microplastics, similar with sedimentation and aerated grid chambers (40-60 percent), while air flotation and membrane bioreactors have been shown to have some of the highest removal rates (over 90 percent) [144, 186, 217]. However, despite an extensive review of the available options, Ngo et al. [217] concluded that currently it is not possible to identify the most efficient and effective technology due to gaps in knowledge and data availability.
- Photo-catalysis, degrading enzymes, nano adsorbents and nanomembranes are other possible options, however they too require substantial further research and testing [144, 218].
- Herbort and Schuhen [219] have proposed the use of novel inorganic-organic hybrid silica gels that have the capacity to remove hydrophobic pollutants, such as microplastics from the WWTPs wastewater. These methods may be proven to be affordable and efficient, however further research is required [219].
- Many of the above treatments remove large amount of microplastics, however fail to remove microfibres. Electro-oxidation has been shown to be relative effective at removing microfibres [144].
- Kole et al. [186] has also suggested that the use of separated sewer systems, where road runoff gets distributed directly into the aquatic environment, should be limited in order to reduce the amount of tyre wear particles entering the marine environment. However, in the same study authors highlighted that such an approach would be very

costly and potentially difficult to implement in the short term as it would require substantial increases to the capacities of WWTPs.

- Many of the above treatments address the issue of microplastics in the WWTP's effluent, however few address the issue of microplastic contamination in the sludge. Mahon et al. [202] explored the effects of WWTPs treatment on the microplastics availability in the sewage sludge. They discovered that anaerobic digestion lead to lower microplastic abundance in comparison to the lime stabilization approach. They have highlighted the need for further research in understanding how anaerobic digestion can be used as a method to remediate microplastic environmental contamination [183, 202].

6. ROUNDTABLE SUMMARY

A round table workshop was held in two parts on the 27th and 29th October, 2020 via video conferencing due to the travel limitations imposed by the COVID-19 pandemic. Key representatives from state and Commonwealth governments, researchers, industry bodies and non-governmental organisations attended. The roundtable provided an opportunity to seek feedback on the key sources of microplastic pollution; explore the current state of scientific understanding on these sources; and consider various options for managing and mitigating impacts of microplastics in the Australian marine environment. This section provides a summary of the discussions on the broader topic of microplastics and the key sources identified in this report.

In general, some participants suggested that reliable data on the impacts of microplastics is still missing, others highlighted that the issue may be greater with nano-particles that can penetrate cell membrane and lead to serious health issues in humans. There was also a suggestion that impacts on human health do need further research. It was noted that in some of the categories a broader focus is required – for example, not just pellets, but flakes, powder, chips etc., to include all types of plastic feedstock. A range of possible options of management and mitigation approaches based on the feedback gathered from the roundtable discussions has been summarised in Appendix 1 and 2.

7. BROAD OPTIONS

Our framing of options for the Australian context follows a traditional categorisation:

- ***Legislation*** enacted by the Australian or by state/territory governments, using mutual recognition and model legislation (recognising that such approaches may be criticised within state parliaments with respect to constraints on their ability to amend or review such legislation). Legislation can reflect national goals such as the *Product Stewardship Act 2011*. This can include a regulatory model that supports co-regulation; for example an industry-based product stewardship scheme that is underpinned by regulation. There is a need for legislation that provides the basis for agreed standards (as seen in each category above).
- Use of ***cross jurisdictional (intergovernmental) frameworks*** that allow broad principles and agreements to be developed and applied as appropriate, with collaboration with industry peek bodies in each of the microplastic source categories. A key we believe would be the concept of subsidiarity – that is state /territory or local government actions should be consistent with high level principles. Such framework should be subject to regular review.
- Support for ***codes of practice*** in sectors/industries, developed through voluntary industry action and establish standards/certification/ratings.
- We also recognise that ***community/consumer engagement*** enhances behavioural change and responses. Engagement with human health and behavioural experts, non-governmental organisations and the education sector to inform community understanding of the sources of microplastic pollution.
- Support for ***industry innovation*** towards a circular economy by addressing product stewardship and extended producer responsibility.
- Finally, there are substantial knowledge gaps in quantitative data for every major source and pathway of microplastics into the marine environment examined in this report. There is also little research to date on the understanding of the effectiveness of mitigation and management solutions. Therefore, ***prioritising quantitative, replicable, solution-focused research*** should be one of the primary targets in addressing the issue of microplastics in the marine environment.

These categories are not mutually exclusive and can provide a useful form of hybrid governance, where legislation is supported by market and community oriented elements. These arrangements are present in co-management, private-public partnerships and private-social partnerships.

In a hybrid governance approach legislation is still a key element but helps frame relationships and outcomes. Hybrid governance provides opportunities as well as challenges for traditional regulatory options.

This review has identified a number of options to address microplastics that are applicable to most microplastic pollution sources and pathways. These are illustrated in Figure 1. Table 1 summarises potential options for the key areas identified in this report. Understanding the scope and scale of the problem is critical and ongoing research will be needed to inform policy options.

8. AREAS FOR POLICY DEVELOPMENT

We recognise that there are information gaps related to both the upstream and downstream management of microplastics. Addressing these gaps is a key step in developing policy options directed at mitigating the impact of plastics on marine environments.

- Noting Australian actions on microbeads, what lessons that can be taken from this success? Can these lessons based on voluntary industry approaches be applied more generally to other types of microplastics?
- Develop a targeted research program (such as the CSIRO's Plastic Mission) to address current scientific and knowledge gaps, recognising the significant information gaps identified in this report.
- Build on commitments from Australian governments to act on plastic pollution and support collaborative work with industry on the sources of microplastics identified in this report, based on deep and broad industry consultation that is embedded in similar EU processes.
- Develop a monitoring protocol for sewage sludge related to microplastics in response to the challenges in sewerage and wastewater management processes in providing pathways for microplastics to enter the marine environment. This can build on and help sustain current work such as the National Outfall Database (https://www.outfalls.info). This database was established by the Clean Ocean Foundation and supported by funding through the National Environmental Science Program (NESP).
- Support ongoing consumer education on microplastic pollution, however, targeted at specific microplastics categories with support from industry peek bodies, recognising that consumer behaviour is a key to long-term change and reducing the level of microplastic pollution.
- Continue processes to provide a legislative focus to management of microplastics. This should include working with industry on addressing extended producer responsibility in developing responses to manage the release of microplastics.

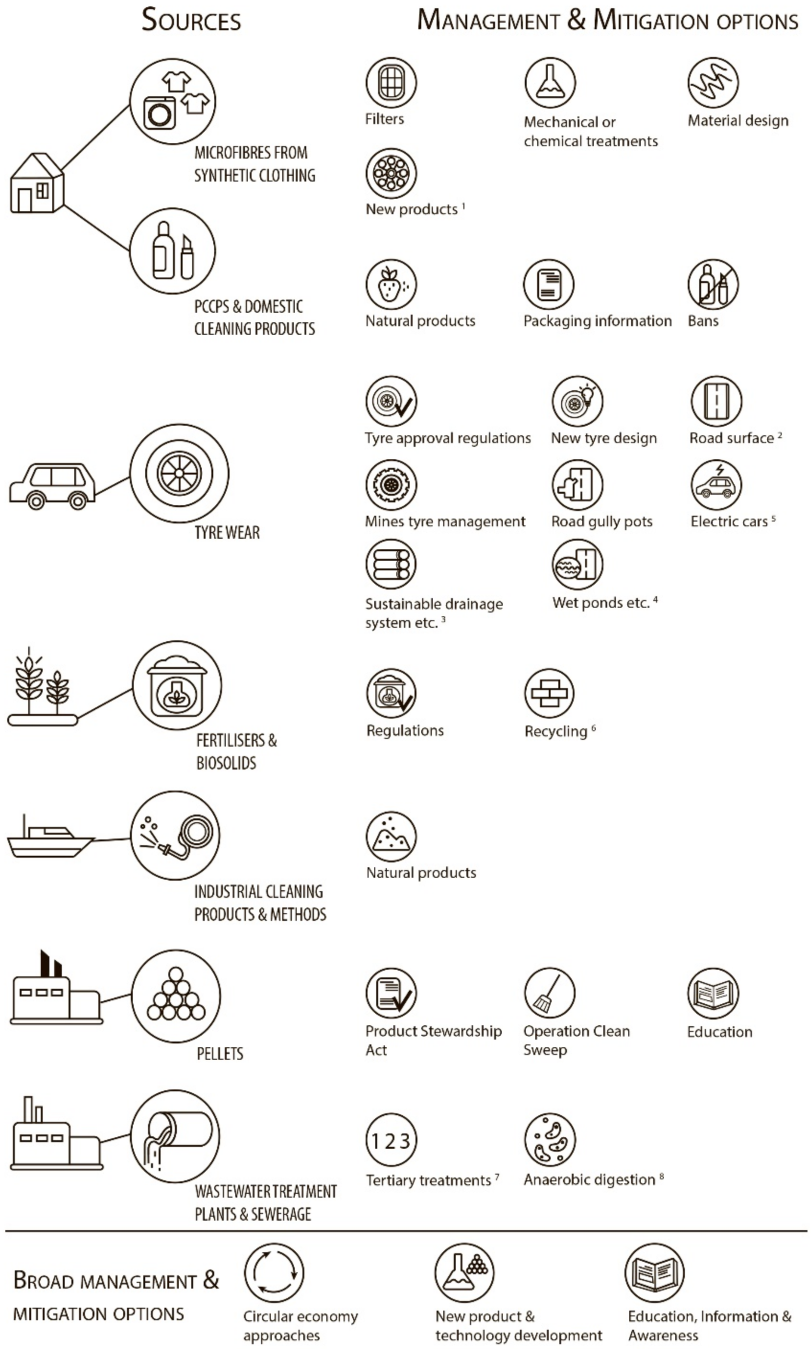

Figure 1 Sources of microplastic pollution in the marine environment and possible mitigation and management options.

[1] A range of new products have been developed that claim that they can reduce microfibre loss during washing (e.g. Coral Balls, Guppy Friend bags)
[2] For example, Open asphalt concrete has been suggested to reduce tyre wear
[3]A range of downstream measures have been implemented with variable degrees of success and cost, such as sustainable drainage systems and compact technical treatment units
[4]Various Road engineering solutions are available, such as wet ponds and sorption of dissolved pollutants through infiltration
[5]Electric cars are believed to have a potential to cause to higher tyre particle wear due to increase weight. Engineering solution to reduce battery weight are needed. Self-drive cars are believed to cause lower tyre wear particle emissions
[6]Proposal for full bans on the use of biosolids as a fertiliser, replacing this use by recycling biosolids in the fire brick production

[7]A large variety of WWTPs treatments are available with various degree of efficiency in microplastic removal: sand and anthracite coal filtration, activated sludge, sedimentations, aerated grid chambers, air flotation and membrane bioreactors¸ photo-catalysis, degrading enzymes, nano adsorbents and nanomembranes etc. Not one treatment has been deemed superior due to lack of data.
[8] Anaerobic digestion with the use of microorganisms and/or fungus
Infographic produced by A. Tushentsova

Table 1 Summary of the options currently implemented or proposed for each of the discussed microplastic sources

	Options categories				
Sources	***Legislation***	***Incentives: Social and Commercial***	***Public Awareness and Education***	***Technology and Innovation***	***Section***
PCCPs and cleaning products	✓✐	✓✐	✓✐	**NA**	5.1.2
Synthetics	✓✐	**NA**	●✐	**!!!**	5.2.2
Tyre wear	●✐	**NA**	●✐	✓ **!!!**	5.3.2
Fertilisers and Biosolids	●✐	**NA**	**NA**	● **!!!**	5.4.2
WWTPs	●✐	**NA**	**NA**	✓ **!!!**	5.6.2

Note: "✓"=implemented in Australia or elsewhere; "●" = proposed, level of implementation was not established; "✐" = further research on effectiveness is required; "!!!" = substantial lack of data; "NA" – not available, implies that possible options have not been discovered during this literature review

9. CONCLUSION

Microplastic pollution in the marine environment has attracted international, national and local/community concern. Considerable efforts are being made to address this problem at these different scales of decision making. We note in this review the program of work and initiatives in the European Union, as well as the work being done by non-governmental groups. This review has emphasized the complexity of the sources and pathways of microplastic pollution in the marine environment, highlighting in particular, the challenge in managing the impacts of microplastics. Moreover, it has uncovered large knowledge gaps in this field for all microplastic sources and pathways. Understanding the scale and scope of microplastic sources and pathways as vectors to the marine environment is critical to address current knowledge gaps.

We identify investment into quantitative, replicable, solution-focussed research as a key priority action. However, we invoke a precautionary approach and advise that current knowledge gaps should not be an obstacle to the implementation of some of the currently available mitigation and management measures. We also recognise the current commitments by Australian governments and industry to address this issue of plastic pollution and suggest that hybrid governance responses, linking to existing legislative and policy commitments can provide a framework for future actions.

APPENDIX 1. ROUNDTABLE SUMMARY: SECTOR SPECIFIC COMMENTS

	Government Action	***Incentives -social and commercial***	***Public Awareness and Education***	***Technology and Innovation***	***General Issues***	***Key Knowledge Gaps***
Microfibres and microbeads	International collaboration in the product stewardship area and regulations on the quality of imported products should be investigated.	It was suggested that other industry representatives, such as washing machine and filter manufacturers should be brought into further discussions.	There was generally strong agreement that education and provision of information options would work well in this field, including general public education on presence and harm of microplastics and ways to reduce emissions and industry staff training in the recycling options (e.g. medical industry).	Some views were that options such as filters in washing machines were not an effective way to tackle the problem, as they may be costly and the "end-of-life" of these products is unknown. Due to this reason benefits are not clear. Others highlighted research that demonstrates effectiveness of filters and suggested that further work is required to develop appropriate way of disposal of this product at the "end-of-life".	Need clear definitions of terms e.g. microbeads have been defined in terms of rinse-off products but many wipe-off products also contain microplastics. Similarly, little attention has been given to the industrial cleaning products and sandblasting media products.	There was a strong push for robust scientific data collection on microplastics sources and pathways. Some members of the group highlighted that focus was only on microbeads in wash-off cosmetics, while little consideration has been given to other sources of microbeads. The importance of science-industry-policy communication and collaboration has been emphasised
Pellets	There is a need for more transparent government preproduction pellets procurement policy, which encourages environmental best practice from industry.	The whole preproduction pellet supply chain needs to be engaged. Logistics companies in some cases contribute to larger spills than manufacturing.	Need to identify where in the supply chain where are the highest risks of pellet loss.	There is a need to improve transport of pellets and other logistical parts of the supply chain that would reduce loss, for example use of catch trays under valves.	Need to identify who is responsible for spills, and have stronger compliance regulations.	Further research on the potential toxicity of pellets, and their breakdown. Pellets adsorb toxins while in the environment – International Pellet Watch - map shows levels of DDT, PCBs etc from pellet samples from Sydney Harbour and Port Phillip Bay.
Tyres	Need for new tyre standards in Australia and regulation needs to be developed/reviewed on allowable wear and tear (as it is in other countries).	Most approached target recycling of tyres but not microplastics pollution from tyres. Should be a whole life-cycle consideration involving all in the supply chain.	Public awareness needs to be raised regarding tyre associated microplastic pollution as a priority, as people generally do not consider tyres to contain plastic.	Also need to consider the wear of different tyre types and the impact of different road surfaces on tyre wear. Have any scientific tests been done in Australia?	Identified as primary, but poorly understood source. Chemical and molecular composition of tyres needs to be better understood before we can properly understand the impacts of tyre wear, as does the molecular	There is a need to quantify how tyre dust contributes to the overall microplastics load. Further research is needed into alternatives and whether they are any better than what is used now.

	Government Action	*Incentives -social and commercial*	*Public Awareness and Education*	*Technology and Innovation*	*General Issues*	*Key Knowledge Gaps*
	There seems to be no transparency around the makeup and performance of imported tyres. Are there any international tyre manufacturing standards? Consumers are therefore not empowered to make good environmental choices when they choose a tyre. Tyre and Rim Association of Australia mentioned as a relevant peak body.		Consumer education on tyre wear also considered important. Educating truck drivers separately on when to change tyres, tyre pressure and how to drive to reduce tyre loss is important as their tyre composition is different. QLD study showed changes to tyre pressure and load distribution resulted in a 20% benefit.		composition of particles in the environment.	It needs to be clear what is the actual problem here – tyre microplastics? Tyre dust? Is the amount coming from tyres as bad as the microplastics coming from roads?
Fertilisers and Biosolids	Need for stronger import regulations to ensure Australia does not import products containing PFAS/PFOS contaminants. Consistency across states, and local governments through an intergovernmental approach would be helpful to allow standards to be set and reporting to these standards.	Develop incentives to encourage industry and consumer responses to reduce use of plastics.	Community education – avoid placing plastics in waste water stream so to reduce biosolid contamination.	Development of alternative bindings.	Characterisation of (micro) plastic waste in biosolids and fertilisers is a key issue. Visual identification can be incorrect, difficulties in characterisation are micro and nano size particles. Develop standard techniques for characterisation, understand what type of particle that often need microscopy and complex analytical/laboratory methods.	Need for standard methods in research and data collection.
Waste Water Treatment Plants	Developing a national reporting standard for WWTPs and use these reports as baseline indicators to see whether upstream policy or	Actions to reduce level of plastics in waste water stream.	Solutions need to be looked at upstream, including incentives and education to reduce loss from textiles and beauty industry (also supported	WWTP should be used to measure environmental health and effectiveness of policies implemented on the source up stream. Development of filtration systems and potential of	Upgrades are costly and are not a short term viable solution. While upstream approach was identified as most effective, the issue was raised that most of the textiles	More research is required to determine the success of different treatments used at different WWTPs. Success of different treatment regimes, e.g. mechanical versus biological treatments, types of filters used need to be

	Government Action	***Incentives -social and commercial***	***Public Awareness and Education***	***Technology and Innovation***	***General Issues***	***Key Knowledge Gaps***
	awareness interventions are working.		by fertilisers & biosolids groups).	photo-catalysis, degrading enzymes, nano adsorbents and nanomembranes.	are produced overseas and hence Australia would be in need of the overseas partners to address this issue.	analysed. The mass balance of microplastics (and material types) between input and output at each stage of treatment at a WWTP also needs consideration. There is a paucity of data regarding this. The issue of the research funding was also raised.

APPENDIX 2: BROAD OPTIONS

- Participants recognised three broad categories of options are available: avoid; intercept; re-design.
- Overall, there was limited support for total bans. Such option was not seen as viable, due to the lack of alternatives, possibility that alternatives may lead to further negative impacts (e.g. environmental impacts of cotton) and toll on the industry.
- There was also a concern that bans on some materials in some industries may lead to the illusion that the problem has been fully addressed, but without a solid understanding of true sources and pathways bans just in some area may lead to misleading feeling of safety.
- There was, however, a suggestion that some sources do lack legislation in Australia (e.g. tyre, fertilisers and biosolids) and they need to be reviewed not just from safety perspective but environmental. ISO and Australian and New Zealand standards are in place for tyres but these focus on safety rather than environmental considerations. Upgrading of standards needs to be undertaken in collaboration with other countries for maximum impact and in recognition that manufacturing occurs outside of Australia.
- There was support for incentive approaches across most themes, noting that they had received general support from different sectors.
- There was generally a strong support to the education and awareness raising approach across all themes: public and industry, including nudging approaches and product stewardship. However, a concern was raised that nudging approaches would only work if there is an alternative; in some industries (e.g. medical) there are currently no-viable alternatives available. It was recognised that advocacy groups could be used in education campaigns
- Intercept options (e.g. filters that allow capture of particles) have received general support, especially from some members of the microfibres group and WWTP group (e.g. washing machine filters, in-wash microfibre capture devices). However, there was a concern raised that some options (washing machine filters, recycling tyres in play-grounds) do not fully address the issues, as the new products would also have end-of-life and question arises what happens to the product then. A question was also raised about who would be responsible for the additional costs of this technology.
- Recycling approaches have also been highlighted by several groups (e.g. recycling of items used in medical industry, recycling of microplastics in concrete), but as above the issue of end-of-life of these products was also raised. There was also a concern that the recycling sector has weaker regulations.
- Looking into product redesign that would reduce loss of microplastics was also supported by several groups (e.g. Patagonia clothing company).
- Product stewardship and design standard has been highlighted as a priority approach by several groups (microfibres, WWTP, tyres, fertilisers)
- The development and promotion of bioplastics was noted, recognising the importance in identifying the type of bioplastics and its potential impacts.
- There needs to be consistency across states on the regulations (noted particularly in the fertilisers &biosolids and pellets themes).
- Universities can play a major role in the innovation and education approaches by setting up “innovation hubs” that could target community education and development of

approach that minimise loss, maximise capture of lost particles and investigate viable recycling options.

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