Plastics, the Environment and Society

Thompson, Richard C.; Pahl, Sabine

Published in:
Energy Storage Options and Their Environmental Impact

DOI:
10.1039/9781788013314-00177

Publication date:
2019

Document version:
Peer reviewed version

Citation for published version (APA):
Thompson, R. C., & Pahl, S. (2019). Plastics, the Environment and Society: Current Consensus and Future Directions. In *Energy Storage Options and Their Environmental Impact* (47 ed., pp. 177-187). (Issues in Environmental Science and Technology; Vol. 2019-January, No. 47). Royal Society of Chemistry. https://doi.org/10.1039/9781788013314-00177

This is a copy of the accepted paper as submitted for publication. Readers are advised to refer to the final version of the paper which can be found at

https://pubs.rsc.org/en/Content/Chapter/9781788013314-00177/978-1-78801-331-4

Abstract

In less than 60 years, plastics have transformed our daily lives. Usage is increasing and now exceeds 330 million tonnes per annum. In this concluding Chapter we summarise current understanding about the benefits and concerns of plastics usage and look to future priorities, challenges and opportunities. It is clear that plastics bring many societal benefits and offer the potential for further advances in medical and technological applications as well as carbon reductions. However, it is also widely acknowledged that current production, use and disposal of plastics is not sustainable. Our understanding of the issues associated with end of life plastics has increased considerably over the last decade. It is now clear that plastic debris has accumulated on a global scale and is present in considerable quantities even in remote locations such as the arctic and deep sea. Plastic debris is frequently encountered by wildlife, often with harmful if not fatal consequences. There are emerging concerns about the impacts of nanosized plastic fragments and preliminary evidence that large items of litter can have negative consequences for human wellbeing. Public, and policy interest in the topic is unprecedented and funding is being made available to address the issue. However, while the suite of potential solutions is well recognised, there is no one size fits all solution. In the current thirst for action, a major challenge is matching the most appropriate solutions to particular aspects of the problem. In addition we need to consider the role of society and the processes of social perception and influence amongst a range of actors. This is

critical because unless the efficacy of solutions is properly evidenced and understood there is a significant risk that interventions taken in haste will not be socially acceptable and/or may lead to unintended negative consequences.

9 Issues in Environmental Science & Technology, Volume 46

Plastics, the environment and society: current consensus and future directions

[1]Professor Richard C. Thompson and [2]Dr Sabine Pahl

[1]Marine Biology and Ecology Research Centre, School of Biological and Marine Sciences, [2] School of Psychology, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK

Email: [1]R.C.Thompson@plymouth.ac.uk; [2]sabine.pahl@plymouth.ac.uk

Table of contents

9.1 Plastics as materials

Plastics are synthetic or semi-synthetic organic polymers, that are typically lightweight, strong, inexpensive, durable and corrosion-resistant [1, 2]. Most plastic items are composed of hydrocarbons derived from fossil oil or gas feedstocks. During the conversion from resin to product, a wide variety of additives (such as fillers, plasticizers, flame retardants, thermal stabilizers, antimicrobial agents and colourings) may be added to enhance performance and appearance [3]. As a consequence, plastic materials can take many forms including rigid items together with more flexible films, adhesives, foams and fibers. The most commonly used polymers are high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP) and polyethylene terephthalate (PET), which cumulatively account for approximately 90% of total plastic production [4] (see Chpt 1 this volume).

These plastic materials can be made into a vast range of products that bring numerous societal benefits, especially in healthcare, agriculture, transport, construction and packaging (PlasticsEurope, 2016; Chpt 1 this vol.). The versatility of plastic materials has resulted in a substantial increase in their use from 5 million tons globally in the 1950s to over 330 million tons today [3, 4]. It is because of this versatility that plastics have considerable potential to reduce the human footprint on our planet; for example as light weight components that can reduce fuel consumption in transportation, or packaging that can considerably reduce damage and waste, especially of perishable food and drink. A key benefit of plastics is their durability; yet around one third of production is of single use items, that are discarded within a year or so of production. As a consequence end of life plastic items are accumulating in the environment, as well as in landfills [5].

9.2 Plastics as waste and litter

It is clear that plastic debris, including microplastic, now contaminate habitats from shallow water to the deep sea and from the poles to the equator (Chapter 4). This debris is present on shorelines, in the water column, in sediments and in organisms [6-8]. The majority of plastics are very resistant to degradation and hence, assuming business as usual, the quantity of plastics in the marine environment will continue to increase.

Plastic litter is extremely heterogeneous in terms of polymer type, size, shape and colour. For example, fishing nets can be 100s of meters in length while microplastics are typically described as items less than 5mm and fragments just a few micrometres in size have been isolated form environmental samples [9] (Chapter 4). It seems likely that even smaller nanoplastic particles also occur in the environment (Chapter 3), but it is not currently feasible to separate and identify plastic particles of this size from complex environmental mixtures [7, 10]. There have been several attempts to quantify the amount of plastic in the ocean on a global scale, but there is a lack of consensus and it has been suggested that there may be as yet unidentified environmental sinks where substantial quantities of plastics have accumulated [8, 11]. A study modelling mismanaged plastic waste discharged from the land estimated annual inputs to the ocean of 4.8–12.7 million tonnes of plastics globally. Whereas empirical counts of litter in particular environmental compartments indicate up to 236,000 tonnes, equivalent to 15–51 trillion small particles [12]. There are considerable challenges in extrapolating from very limited empirical data to make predictions about spatial patterns of distribution and some of the best estimates available have uncertainty levels of over 100 fold [12].. Assuming business as usual, Jambeck et al. (2015) predict a three-fold increase in the amount of plastics in the ocean between 2015 and 2025

9.3 Environmental impacts of plastics

Plastic debris can affect marine organisms through entanglement and ingestion [13]. Impacts vary according to the type and size of the debris and can occur at different levels of biological organisation in a wide variety of habitats [9, 14, 15]. Over 700 species of marine organism, including marine mammals, birds, fish and invertebrates, are known to encounter plastic debris. This can result in severe physical harm and death, or have more subtle sub-lethal effects on behaviour and ecological interactions [13, 15, 16]. Ingestion is widely reported and is common for small fragments and items of debris, such as bottle caps, balloons and sewage-related debris. By contrast entanglement is typically associated with abandoned, lost or discarded fishing gear and accounts for many reports of harm or death on a global scale [17].

The potential for ingestion is greater with smaller pieces such as those in the microplastic and nano plastic size range (< 5mm, see Chapters 3 and 5). Quantities reported per individual are typically low in the environment, but laboratory studies at higher concentrations indicate ingestion of microplastics can compromise the ability of planktonic organisms to feed [18] and the ability of marine worms [19] and fish [20] to gain energy from their food. Concern have been raised that microplastics might facilitate the transfer of organic and inorganic chemicals to biota [21-23]. However, current evidence suggests that microplastics are not likely to be a major vector in the transport of chemicals to organisms from seawater [24, 25]. An additional pathway is the release of potentially harmful additives, such as flame retardants and plasticisers (see Chapters 6, 7) that were incorporated into plastic items during manufacture [21, 26]. These additive chemicals can be present at high concentrations and there is evidence that some can transfer to biota upon ingestion [27], but little is known about the potential for any associated toxicological effects.

Most laboratory studies demonstrating effects from microplastics have used concentrations higher than those currently found in the environment [28]. While these experiments inform our understanding of thresholds in relation to future levels of contamination, they do not provide clear evidence of current environmental consequences. Discussions in Chapters 6 and 7 clearly indicate the need for longer term chronic low dose exposure studies as well as evaluation of nanoplastic particles which have the potential to be transferred across cell membranes and could accumulate in specific tissues [10]; coupled with substantial surface area, such particles may present different challenges not those described for larger plastics (Chapter 3).

While there are still considerable knowledge gaps concerning the potential environmental impacts of microplastic and nanoplastic it is clear that encounters between organisms and macroplastic litter negatively affect wildlife and that a substantial proportion of some populations can be contaminated with plastics (see Chapter 5). For example, extensive data set for the Northern Fulmar indicated that over 95 per cent of individuals in some locations had plastic debris in their digestive tract. Scaling up evidence from impacts on individuals to population-level consequences is challenging in the field since it is almost impossible to isolate the effects of plastic debris from other environmental impacts.

Summarising across all of the evidence, the EU Marine Strategy Framework Directive (MSFD) expert group on marine litter recently concluded that plastics present a "large scale and serious threat to the welfare of marine animals" [15]. Building on this it seems likely that there will be consequences at higher levels of biological organisation. Localised field experiments indicate even a single plastic carrier bag causes smothering which can alter the relative abundance of sediment-dwelling organisms as well as the ecosystem services they provide [29]. From a risk assessment perspective more work is needed to model the probability as well as the severity of encounters. This has recently been done for encounters between turtles and abandoned fishing nets in waters to the north of Australia [30]. However, our wider ability to construct models of this type is limited, by a lack of understanding about some the specific types of harm caused by different types of plastic debris and detailed empirical data on the current distribution of this plastic.

9.4 Socio economic Impacts of plastics

Plastic litter can impact on fisheries reducing and damaging catches as well as damaging vessels. The types of litter that are most frequently caught in fishing gear are ropes and other plastics [31]. As well as effects on the operation of fishing vessels there are concerns about contamination of the fish stock; with 49 commercially important species including sardines, herring, hake, whiting and red mullet being known to ingest microplastics [7, 16]. Despite this widespread occurrence, the quantity of plastics currently reported in seafood is low, with a contaminated individual typically containing one or two items of plastic and it seems unlikely that these levels of microplastic would be harmful to humans. However, there is concern in the fishing and aquaculture industry that even small quantities of plastic might be perceived negatively by consumers and affect marketability [7].

A recent EU-wide survey demonstrated that 95 per cent of visitors noticed litter on either, most, or every visit to the coast [32]. In another study, visitors regarded litter as very annoying and it influenced the locations they chose to visit [33]. The public are concerned about the accumulation of both macroplastics and microplastics in the environment and regard litter as an important current environmental problem [32]. There is evidence that even relatively small amounts of macroplastic litter can have a negative effect on what psychologists would describe as the *restorative* value, from the perspective of human well-being, of a visit to the coast [34]. Clearly, the frequency of these negative impacts will increase in relation to increasing levels of contamination.

9.5 Solutions and remaining challenges

There are already a range of policy measures and international conventions relating to marine litter and waste management, however based on the scale of the problems and the levels of concern outlined in this chapter it would appear that the measures currently in place are insufficient. In some cases there are difficulties associated with enforcement, for example the regulation of dumping at sea (MARPOL Annex 5). It is also essential to better understand the relative importance of the various sources of litter and to assess how these vary regionally, as well as adopt a broader systems perspective to analyse the complexities of plastic flows from society to the natural environment. Contamination of the ocean by plastic is a global problem. Although there is evidence that considerable quantities of litter remain relatively close to their point of origin to the ocean, it is also clear that litter does not respect international boundaries and that it can travel considerable distances. In addition, policies and other 'top-down' instruments work best when in line with public awareness and opinion, and are based on a knowledge of systems and behavioural factors that contribute to the problem. So while it is important to minimise any direct inputs of plastic litter to the ocean on a local scale it is also clear that effective long term change can only be achieved by working across borders, boundaries and sectors, taking a systems perspective and using instruments focusing on both top-down (such as regulation) and bottom-up (such as communication campaigns) as triggers of change.

There are gaps in our knowledge about the full extent to which plastic litter and in particular, microplastics and nanoplastics cause harm at current environmental concentrations (Chapters 3 and 5); however there is general consensus that marine litter is problematic and that action is required to reduce the quantity of plastics escaping to the oceans. Hence, as well as further defining the scale of the problem it is important to address knowledge gaps relating to solutions; such as research focused at changing behaviour and practices. Plastics are very useful materials that bring an extensive range of societal benefits (Chapter 1). Plastic production has increased considerably over the last few decades and, as its carbon, source currently uses around 4% of world oil production. However, extensive use of plastics *per se* is not the sole cause of the problem, it is the decisions made about how to produce, use and dispose of plastic items that result in waste and litter. Plastic pollution is entirely caused by human actions; there is no natural sources that contribute to the problem (in the way that there is, for example, with oil released to the environment from natural seeps). Contrary to other environmental issues, such as climate change, plastic pollution is tangible and visible and there is no notable public scepticism over the issue. The benefits society derives from plastics could, in principle, be completely decoupled from the materials escaping into the natural environment. This is a good starting point for change as appropriate measures should in theory meet with wide public acceptance.

As we have discussed so far, plastics research still faces considerable challenges and a number of research questions remain. One of the more intriguing, and less researched, challenges is around negotiating the interface with public opinion and the media, as well as understanding social influences processes and behaviours better, which are within the realm of the social and behavioural sciences [35, 36].

Plastic pollution has recently seen an exponential rise in interest and debate in the public domain. For example, in the UK, plastic pollution appears to have been thrown into the headlight following the broadcast of a very popular nature programme (Blue Planet II) that explicitly discussed plastic impact on ocean wildlife, presented by a highly trusted naturalist (Sir David Attenborough) and accompanied by impactful visual images, to the extent that the UK Environment Minister released a statement saying he was haunted by images from the documentary (see Guardian Environment, December 2017, see Pahl et al., 2017)[36].

Having been the focus of considerable natural sciences research for decades, this rise in interest has taken some by surprise, and it has triggered discussion among scientists and policy makers questioning whether there is currently too much focus on plastics to the detriment of other pressing environmental issues. There is no easy answer to this question but in this section we will take a social and behavioural sciences perspective that might help understand these social processes.

We use plastics widely in modern society because of the multitude of benefits plastic materials bring including versatility, cost and convenience (see: Chapter 1) and these benefits drive the decisions and behaviours of actors along the production and consumption chain [35, 36]. For example, plastic microbeads were introduced into cosmetic products with scouring properties (e.g., facial scrubs) for cost, consistency of supply and performance and because they happen to be anti-allergenic, as opposed to some previously used natural substances. This would be the producer perspective. However, this was not accompanied by clear labelling and public awareness of ingredients so when NGOs began to campaign about the issue the public responded with considerable revulsion to the plastic content in these products. In our own research we showed plastic microbeads extracted from a range of common products to members of the public, they expressed shock, found this unnatural and fake and spontaneously wanted to explore the after-use fate of the product, e.g., impact on marine life[37]. This is an example where internal product design decisions might not have been tested with end consumers and could lead to loss of trust in the industry, especially in the sensitive context of personal care products. It has also been observed (see Chapter 8) that some materials are used because they are thought to enhance the presentation and thus customer appeal, such as black plastic containers for some food items. Again, this could backfire as customers become more savvy about recycling and passionate about defending the environment. These trade-offs are not straightforward and require careful analysis of empirical social evidence, but they also provide an opportunity for industry to consider products from a more holistic perspective and then communicate this so as to become a frontrunner by innovative labelling.

Alongside this there is also a broader need to better understand the behaviours that lead to littering as well as those that lead to engagement in recycling. [35] With rates of recycling for manufactured plastics of around 9% there is considerable scope for improvement (Chapter 8). Recent debate has turned to China / Southeast Asia as the regions with globally the largest input of plastic items to the oceans (Jambeck ref). While these estimates reflect an accounting-type approach, the complexities detailed in the Jambeck et al. analysis have been considerably underreported in the media, for example the differences in waste management systems and the fact that many countries with very good waste management systems still do not recover and recycle valuable materials. Finger pointing at individual nations is not helpful when we need to work together. In our view more developed countries have a moral obligation to demonstrate resource efficiency.

Historically, most measures to reduce marine litter have focused on end-of-pipe solutions. Marine litter is a problem in the sea, but it mostly originates on the land and in order to develop long-term solutions there is a need to educate and change behaviours along the supply chain. Mechanisms to facilitate dialogue between stakeholders would be very worthwhile, for example, linking product design to recycling capability could directly facilitate more circular, rather than linear, use of plastic materials in the sense of a circular economy. Around 40% of production is of single-use items and these items account for a large proportion of waste and litter. Most plastics are inherently recyclable, yet many single use items are not compatible with recycling. A key challenge therefore is to ensure end-of-life disposal is appropriately considered at the design stage (Chapter 8). One way of achieving this might be to establish a Plastics Stewardship Council, similar to FSC or MSC that would endorse responsible material use. This is important because if more end-of-life material can be recycled it will not only reduce the quantity of waste in managed systems and the quantity escaping to the environment as litter, it will also reduce use of fossil oil and gas used to manufacture new plastics [38, 39].

There are also actions that could inadvertently confuse or compromise the solutions outlined above. For example, the use of '*bio-based'* carbon obtained from plants grown in agriculture is seen as a sustainable alternative to fossil carbon. Many consumers have enthusiastically adopted products made from materials labelled as bio-degradable. However, altering the carbon source used to make plastics will not reduce the generation of waste or the accumulation of litter, and the consumer experience might rapidly turn negative when a plastic bag intended for re-use by the consumer crumbles into fragments. A more logical and efficient approach is to supply the required carbon by recycling. In addition, designing plastic products so that they degrade or disintegrate more rapidly may, over time, reduce the accumulation of large items of debris, however, such products may compromise the potential for product re-use, contaminate recycling, and accelerate the production of microplastic fragments [40]. It may also undermine consumer acceptability of the product or, worse, trust in producer labelling, in the long run. Hence, the use of degradable, biodegradable and compostable plastics only presents a solution in specific settings where an appropriate receiving environment for the resultant waste is defined, the associated waste collection is specifically managed and the products are adequately labelled to facilitate appropriate disposal.

The benefits of citizen focused activities such as beach cleaning are well recognised from an educational as well as a litter removal perspective [41]. However, there are concerns about the efficacy and viability of large scale mechanical clean-up operations at sea. This is because current rates of entry for litter to the marine environment far exceed the potential for removal by clean-up. An appropriate analogy would be to consider returning to the bathroom to find one's bath overflowing, do you start by mopping the floor or turning off the tap? In our view it is essential that we turn off the plastic tap with some urgency. Furthermore if clean-up is seen as substantive solution it must be acknowledged that there will be a need for such clean-up in perpetuity. Therefore the main priority must be to focus on preventing litter entering the oceans in the first place.

To address this type of challenge we think an inter-disciplinary, inter-sector approach will be necessary to reconfigure how modern societies engage with plastics (Figure 1). Profiting from the current groundswell of public opinion, transformative change could be achieved by harnessing the potential of the Social and Behavioural Sciences to understand the decisions and behaviour underlying the plastics challenge, Arts and Humanities to inspire change, firmly integrated with the natural sciences' evidence base. Beyond integrating different academic perspectives, such an effort should work with stakeholders, practitioners, policy makers and industry. This approach would be able to capture how plastics are currently viewed and managed in society, truly representing the user perspective, and identifying and responding to both intrinsic and extrinsic motivations and constraints along the supply chain. More importantly, the approach can demonstrate how the current situation may change by facilitating evidence-based dialogue with design and waste management, economic and legal studies, arts and other creative disciplines. Looking at the system in such an integrated way has the potential to trigger an irreversible course towards more sustainable design, use and disposal of plastics and could be adapted to other societal challenges.

[FIGURE 1 HERE]

5.9 References

1. J. G. B. Derraik, *Mar. Pollut. Bull.*, 2002, **44**, 842-852.
2. R. C. Thompson, S. H. Swan, C. Moore and F. S. vom Saal, *Philosophical Transactions of the Royal Society B*, 2009, **364**, 1973-1976.
3. A. L. Andrady and M. A. Neal, *Philosophical Transactions of the Royal Society B*, 2009, **364**, 1977-1984.
4. Plastics Europe, *Plastics the facts 2015 An analysis of European plastics production, demand and waste data*, Plastics Europe, Brussels, 2015.
5. STAP, *Marine Debris as a Global Environmental Problem: Introducing a solutions based framework focused on plastic*, Global Environment Facility,, Washington, DC, 2011.
6. D. K. A. Barnes, F. Galgani, R. C. Thompson and M. Barlaz, *Philosophical Transactions of the Royal Society B*, 2009, 1985-1998.
7. GESAMP, *Sources, fate and effects of microplastics in the marine environment - part two of a global assessment*, 2016.
8. K. L. Law and R. C. Thompson, *Science*, 2014, **345**, 144-145.
9. UNEP, *Marine plastic debris and microplastics - Global lessons and research to inspire action and guide policy change* United Nations Environment Programme, Nairobi, 2016.
10. A. A. Koelmans, E. Besseling and W. J. Shim, in *Marine Anthropogenic Litter*, eds. M. Bergman, L. Gutow and M. Klages, Springer, Heidelberg, 2016, pp. 325-341.
11. R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle and A. E. Russell, *Science*, 2004, **304**, 838-838.
12. E. van Sebille, C. Wilcox, L. Lebreton, N. Maximenko, B. D. Hardesty, J. A. van Franeker, M. Eriksen, D. Siegel, F. Galgani and K. L. Law, *Environmental Research Letters*, 2015, **10**.
13. S. C. Gall and R. C. Thompson, *Mar. Pollut. Bull.*, 2015, **92**, 170-179.
14. M. A. Browne, A. J. Underwood, M. G. Chapman, R. Williams, R. C. Thompson and J. A. van Franeker, *Proceedings of the Royal Society B-Biological Sciences*, 2015, **282**.
15. S. Werner, A. Budziak, J. van Franeker, F. Galgani, G. Hanke, T. Maes, M. Matiddi, P. Nilsson, L. Oosterbaan, E. Priestland, R. Thompson, J. Veiga and T. Vlachogianni, *Harm caused by Marine Litter. MSFD GES TG Marine Litter - Thematic Report*, 2016.
16. E. L. Kuhn, R. Bravo and J. A. Fvan Franeker, in *Marine Anthropogenic Litter*, eds. M. Bergman, L. Gutow and M. Klages, Springer, Heidelberg, 2015, pp. 75-116.
17. G. Macfadyen, T. Huntington and R. Cappell, *Abandoned, lost or otherwise discarded fishing gear*, UNEP/FAO, Rome, 2009.
18. M. Cole, P. Lindeque, E. Fileman, C. Halsband and T. S. Galloway, *Environ. Sci. Technol.*, 2015, **49**, 1130-1137.
19. S. L. Wright, D. Rowe, R. C. Thompson and T. S. Galloway, *Current Biology*, 2013, **23**, 1031-1033.
20. T. Cedervall, L. A. Hansson, M. Lard, B. Frohm and S. Linse, *Plos One*, 2012, **7**.
21. C. M. Rochman and M. A. Browne, *Nature*, 2013, **494**, 169-171.
22. C. M. Rochman, E. Hoh, T. Kurobe and S. J. Teh, *Nature Scientific Reports*, 2013, **3**, 3263.
23. L. A. Holmes, A. Turner and R. C. Thompson, *Environ. Pollut.*, 2012, **160**, 42-48.
24. A. Bakir, I. A. O'Connor, S. J. Rowland, A. J. Hendriks and R. C. Thompson, *Environmental pollution (Barking, Essex : 1987)*, 2016, **219**, 56-65.

25. A. A. Koelmans, E. Besseling, A. Wegner and E. M. Foekema, *Environmental Sciecne and Technology*, 2013, **47**, 7812-7820.
26. D. Lithner, A. Larsson and G. Dave, *Sci. Total Environ.*, 2011, **409** 3309-3324.
27. K. Tanaka, H. Takada, R. Yamashita, K. Mizukawa, M. Fukuwaka and Y. Watanuki, *Mar. Pollut. Bull.*, 2013, **69**, 219-222.
28. R. Lenz, K. Enders and T. G. Nielsen, *Proceedings of the National Academy of Sciences of the United States of America*, 2016, **113**, E4121-E4122.
29. D. S. Green, B. Boots, D. J. Blockley, C. Rocha and R. Thompson, *Environ. Sci. Technol.*, 2015, **49**, 5380-5389.
30. C. Wilcox, B. D. Hardesty, R. Sharples, D. A. Griffin, T. J. Lawson and R. Gunn, *Conservation Letters*, 2013, **6**, 247-254.
31. T. Mouat, R. Lopez-Lozano and H. Bateson, *Economic impacts of marine litter*, KIMO (Kommunenes Internasjonale Miljøorganisasjon), 2010.
32. B. L. Hartley, S. Pahl et al. (in press), Exploring public views on marine litter in Europe: Perceived causes, consequences and pathways to change. Marine Pollution Bulletin.
33. R. Brouwer, M. Galantucci, D. Hadzhiyska, C. Ioakeimidis, A. Leermakers, H. Ouderdorp, B. Boteler and P. Fernandez, *Socio-Economic Assessment of the Costs of Marine Litter*, 2015.
34. K. J. Wyles, S. Pahl, K. Thomas and R. C. Thompson, *Environment and Behaviour*, 2015, **15/07/15**, 1-32.
35. S. Pahl and K. J. Wyles, *Analytical Methods*, 2017, **9**, 1404-1411.
36. S. Pahl, K. J. Wyles and R. C. Thompson, *Nature Human Behaviour*, 2017, **1**, 697-699.
37. A. G. Anderson, J. Grose, S. Pahl, R. C. Thompson and K. Wyles, *Mar. Pollut. Bull.*, 2016, **113**, 454-460.
38. R. C. Thompson, in *Marine Anthropogenic Litter*, eds. M. Bergman, L. Gutow and M. LKlages, Springer, Heidelberg, 2015, pp. 185-200.
39. A. A. Koelmans, T. Gouin, R. C. Thompson, N. Wallace and C. Arthur, *Environ. Toxicol. Chem.*, 2014, **33**, 5-10.
40. R. C. Thompson, C. Moore, F. S. vom Saal and S. H. Swan, *Philosophical Transactions of the Royal Society B* 2009, **364**, 2153-2166.
41. S. E. Nelms, C. Coombes, L. C. Foster, T. S. Galloway, B. J. Godley, P. K. Lindeque and M. J. Witt, *Sci. Total Environ.*, 2017, **579**, 1399-1409.

Figure 1) Interdisciplinary approach to uniting academic disciplines to deliver holistic evidence to guide policy and industry toward optimal solutions – maximising material circularity and minimising plastic waste and litter