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Plastic pollution: about time to unify research methods and demand systemic changes

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The issue of plastic pollution is recognised as a pervasive and ubiquitous problem which can pose a threat to ecosystems worldwide and potentially affect human health. In this perspective, we selected the latest research that identifies potential impacts beyond individual species to draw attention on wider biogeochemical cycles and the most fundamental biological processes we all depend on, namely, breathing, feeding and carrying offspring. We highlight the need for uniform research methods, giving examples of protocols and indicator species that should be evaluated by the research community for their potential wide adoption. We stress the need for systemic changes and our role as scientific community to demand changes proportionate to the severity and implications of our findings. We further explore the push and pull mechanisms between researchers and policymakers in relation to the global environmental challenges such as plastic pollution. Finally, we recommend a path of action inspired by the global action taken to address the ozone layer depletion by banning chlorofluorocarbons (CFC).

KEYWORDS

plastic pollution, marine plastic, terrestrial ecosystems, wicked problem, biogeochemical cycles, planetary boundaries, human health

Introduction

Marine plastic pollution or marine litter has become one of the most researched topics in marine pollution research as recently shown by Riechers et al. (2021). The problem is so vast, so complex and so ubiquitous that research has flourished in an attempt to fill the numerous gaps left in this global jigsaw. When searching the literature on marine litter, one is left with a dizzying kaleidoscopic vision, as the more we get into the details, the more complex the problem appears. Each question gives rise to a plethora of other questions which, it seems, need answered before effective mitigation and prevention measures can be taken. This evokes the definition of a wicked problem, as summarized in Wagner (2022) for the case of plastic pollution. The issue is not less pressing within the terrestrial environment, but so far less researched. In this perspective article, we broadly sketch up the problem of plastic pollution on a large scale, looking at biogeochemical cycles and possible effects on ecosystems and physiological processes in humans and other species. We then reflect upon the lack of action, drawing on concepts of wicked environmental problems, leverage points, and the dynamic between researchers and policymakers. We conclude the article by tying together the different ropes looking at the historic success story of chlorofluorocarbons (CFC) to propose a path of action for the research community and policymakers.

Uncertainty: it depends on. . .

How does plastic flow? Where do marine debris come from and end up? How fast and under which circumstances does plastic get broken down into smaller pieces? What chemical pollutants are associated with plastic? What microbial communities grow on plastic to form the plastisphere (Steer and Thompson, 2020)? What are the effects, if any, of plastic ingestion by living organisms? What is the ecotoxicological threshold, for the polymers, associated colorants, chemical additives and "hitch-hikers" (Kirstein et al., 2016)? What are the pathways for their sorption into the food chain? And what other pathways exist for the sorption (Khalid et al., 2021) of plastics and associated chemicals and pathogens? For each of these questions, the answer starts by "it depends . . . ." Indeed, it depends on the type of polymer, on the shape, the density, the size, the weight, the colour of the debris and type of additive (Khalid et al., 2021). It also depends on the topography, weather conditions and within the marine environment, the currents (Chassignet et al., 2021; Strand et al., 2021; Huserbråten et al., 2022). It depends on the species' presence, on the behavior of individual organisms and on the concentration of plastic particles and their associated organic or inorganic compounds (e.g., Jacquin et al., 2019; Lopez-Martinez et al., 2020; Bonanno and Orlando-Bonaca, 2020; Khalid et al., 2021; Pirsaheb et al., 2020; Sönmez et al., 2022). And the list of variables goes on. A problem that is man-made, is totally escaping human comprehension. Indeed, the main challenge is to transcend local data and species-specific knowledge, to globally relevant science on the behavior and the effects of plastics and associated pollutants, that can inform policy-making.

Uniformity in research methods

At the center of this challenge is the lack of uniformity in research methods on plastic. This issue is due to the complexity and early stage of this field and to the ever-changing nature of the environment and the diversity of plastic types, sizes and associated organic and inorganic compounds. However, a consensus on methodologies is the essential first step to enable repeatability, better quality-assurance in review processes and, by extension, knowledge-building. This issue needs to be addressed systematically, for each subfield of plastic pollution research and it should be done now. Perfect methods and protocols might not exist in this field; however, consensus is needed on parameters such as the definition of size ranges, polymer types to focus on, analytical methods and indicator species, and from there recommend worldwide targeted policies, and protocols to monitor the effects of measures and regulations (e.g., Logemann et al., 2022). Various attempts at designing global protocols for plastic research have recently been published such as, among others Farmen et al. (2021) on microplastic monitoring in Arctic regions; Duncan et al. (2020) on the design of "bottle tags" to simulate plastic movement; The European Commission coastline microliter assessment protocol, and the OSPAR (Oslo and Paris Convention) marine litter assessment (European Commission, 2020); Frias et al. (2018) for sediment analysis. Indicator species have been proposed such as *Nephrops norvegicus* (Joyce et al., 2022) and tube dwelling polychaete species in the Oweniidae family (Knutsen et al., 2020). For more detail, Multisanti et al. (2022) offer a comprehensive review of possible indicator species across taxa and advocate the use of a One Health approach to motivate the monitoring of sentinel species. Similarly, within the field of microplastic, various protocols are proposed and discussed. For sediment (Bellasi et al., 2021) and water analysis (Lee and Chae, 2021) a variety of analytical strategies are discussed, while Hermsen et al. (2018) and Tsangaris et al. (2021) present comprehensive protocols for biota analysis. These need to be reviewed by the scientific community and adopted, adapted or replaced. It is also important to involve NGOs and policymakers to create these guidelines, enabling research results suitable for policymakers. Establishing long-lasting international working groups should be the first step, as well as long-term financial support to these.

We need system change, not ecosystem change

The issue of plastic pollution has made media headlines for years but the system change and international regulations required to address this global issue are lagging behind. What can we as scientists hope to achieve in such circumstances? Riechers et al. (2021) used Donella Meadows' leverage point framework (Meadows, 1999) to show that only a very small proportion of journal articles addressing marine pollution dealt with it as a systemic socio-ecological problem. They encouraged researchers to investigate and to recommend changes in the deeper drivers of marine pollution such as proactive and preventive interventions to change values, goals and the intent of the system.

Many studies have documented local effects of plastic on vertebrate and invertebrate species, reviewed in, e.g., Lopez-Martinez (2020); Pirsaheb et al. (2020); Sönmez et al. (2022). In addition, plastic has been hypothesised to impact the Earth as a system, by disrupting wider biogeochemical cycles in the ocean and soils (Villarrubia-Gomez et al., 2018; Galgani and Loiselle, 2021; Rilling et al., 2021). For instance, Galgani and Loiselle (2021) have suggested that plastics in the ocean will ultimately change the balance of primary to secondary producers, the rate of sinking nutrients and the bioavailability of nutrients at deeper levels of the ocean. This combined with warmer temperatures and more acidic conditions, might ultimately have consequences on the carbon cycle and the ability of oceans to act as a sink for greenhouse gases. All in all, there is now backing to take plastic pollution seriously enough to call it a planetary boundary (Villarrubia-Gomez et al., 2018; Arp et al., 2021). An update on the front of Planetary Boundaries for Novel Entities shows that we have now exceeded yet another boundary and that plastic is facilitating this process (Persson et al., 2022). Moreover, the authors conclude that plastic production is closely linked to the planetary boundaries of biosphere integrity and that its production volume is a strong proxy for overall anthropogenic change (Persson et al., 2022). Is it about time to use the precautionary principle to curb the problem?

When it comes to soils, there is evidence of plastic concentration in soils supporting this claim (Zhang et al., 2020; Bastesen et al., 2021; Cyvin et al., 2021) suggesting that soil properties such as

porosity, oxygen levels and pH might be changed by the presence of plastics and that, among others, plants (Wang et al., 2022), invertebrates (Ji et al., 2021) and microbial communities (Huang et al., 2021) might be affected. In general, the terrestrial ecosystems are poorly investigated with regards to the concentrations and effects of plastic pollution (Rilling et al., 2021).

Which systemic changes can we recommend as scientists to halt the input of plastic into the environment? Given the striking diversity of the plastic particles found and the challenges in recycling hybrid materials, would it be unthinkable to put a lid on plastic product diversification, misleadingly termed "innovation?"

Another systemic change that is underreported is the need to reduce our consumption of plastics. Indeed, we cannot assume that in the next years, we will see a surge of collection and recycling infrastructure with associated labour all over the world, which will completely rid us of the problem of "mismanagement." Nor can we expect scientists or industries to invent a "technological fix" that will magically clean up the environment. On the contrary, as our consumption of single-use items increases worldwide, no recycling plant could cope, especially not on island nations or developing countries. Plastic is embedded in almost all aspects of our daily lives, and cutting plastic out seems an overwhelming task, given current trends in global use and production of plastic. The focus should be placed on limiting ourselves to essential single-use plastics (e.g., personal care products and healthcare, hygiene), use of long-lasting easily reusable and recyclable products where no realistic alternative exists. Active involvement of the industry as well as strong policy regulations are needed. Let us consider further the ubiquity of plastic in our lives and how it might impact human health.

Possible human health risks

Plastics are used increasingly in domestic products in the form of fibers, pellets or dust (Henry et al., 2019; Steer and Thompson, 2020; Jenner et al., 2022). One of the most pressing questions about plastic pollution is related to possible human health effects. It is now established that plastic dust is present in the atmosphere, especially in cities, from decomposition of old plastic, presence in building materials and paints, vehicle tyres, *etc.* (Ageel et al., 2022; Nematollahi et al., 2022). Indeed, Jenner et al. (2022) recently quantified microplastic particles in human lung tissue. Prata et al. (2020), p. 7, on the other hand discuss possibilities for oxidative stress and inflammation, disruption of immune functions, neurotoxicity and neoplasia, and conclude that "more studies are needed to fully understand the risk of microplastics to human health." But can we at the same time, already, encourage research into the deep drivers leading to possible health effects?

Ingestion of plastic by humans through drinking water and foods has also been widely documented (e.g., Danopoulos et al., 2020a; Danopoulos et al., 2020b). Although, it may be difficult to carry out research on human health effects of plastics due to ethical consideration, finding a control group (Henry et al., 2019), and problems isolating plastics from other pollutants, if the pathways for health effects can be pinpointed in other species, as reviewed, for example, in Pirsaheb et al. (2020), it does not defy scientific logic to assume that similar pathways exist with humans. One way of going around this issue is by quantifying exposure to plastics in our direct environments.

As a striking example, Ragusa et al. (2020) found the first evidence of microplastic in human placenta. Their study along with one from Sripada et al. (2022), point out that foetus and infants are more than ever exposed to microplastic and associated pollutants from the placenta to breast milk to the very air they breathe, and dust they ingest. Moreover, foetuses and infants might not have a developed enough coping mechanism to exclude these pathogens from their metabolism, as adults (Sripada et al., 2022). The effects are not well understood but it is reported that microplastic may create localised toxicity and trigger immune responses (Sharifinia et al., 2021): Again—"it depends on . . .."

When highlighting the ubiquity of plastics in industrial and household products, clear recommendations for how to reduce these substances should be developed. Henry et al. (2019) recommend including plastic fibre loss from household furniture in sustainability assessments. Woods et al. (2021) developed effect factors for the widely used Life Cycle Assessment tool and Maga et al. (2022) lay out the LCA methodology to include effect and exposure factors. Clear regulations should be issued for the private sector to not only document and limit the use of plastic polymers in their products but also to carry the burden of proof when it comes to safety.

Scientists are sounding alarm bells all around the globe with recommendations of incremental adjustments to the current system (Riechers et al., 2021), while plastic inputs into nature and our bodies are reaching disturbing proportions. What happens after scientific findings are published can be conceptualised by observing other global environmental challenges as described in the next section. But it is time to use the precautionary principle and be bolder in our recommendations.

The role of scientists in policy-making

According to Watson-Wright (2005), scientists and decision makers are ensnared in a "push" and "pull" dance, where scientists draw attention to a problem, policymakers then ask scientists for more information and recommendations and on it goes from there.

Marine pollution was mentioned already by the French author and explorer Jules Verne in 1870. Throughout the 1960s and 1970s, there were reports about marine plastic found in or entangled around birds, turtles, manatees, cetaceans and reports about plastic and micro plastic in general where published (Ryan, 2015). Plastics have now been shown to be present in all the spheres we operate in, from the biosphere, to the atmosphere, the cryosphere and hydrosphere (Kim et al., 2021; MacLeod et al., 2021). Many governments and international organisations then came back to the scientific community to ask for more research (Figure 1). One of the latest, and also widely misinterpreted (in the media) calls for research was by the World Health Organization on the effects of microplastic on human health from drinking water (WHO, 2021).

Scientists are then asked to make policy recommendations, and this is where we as researchers could make an impact. However, most articles conclude that we need more research or better management and clean-up, i.e., low-impact measures

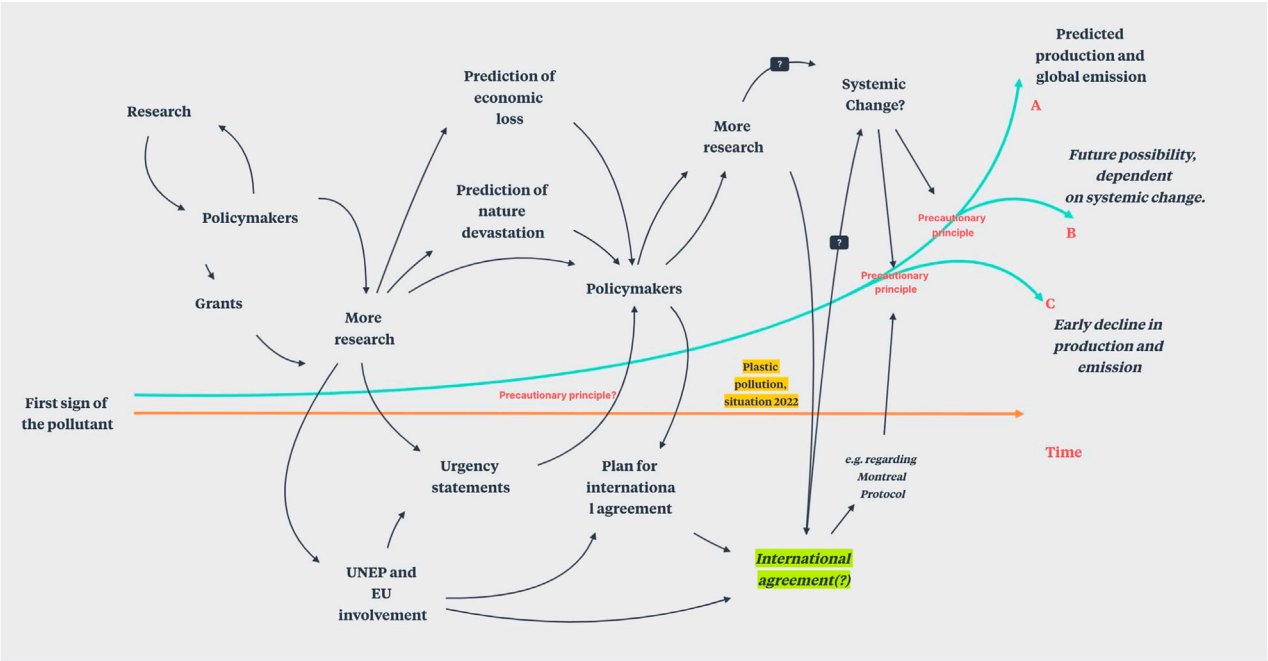

FIGURE 1
Simplified and conceptual drawing of the push-and-pull dynamic between researchers, policymakers and the ultimate development of international agreements. The *x*-axis represents time, while the green line shows how the pollutant increases in production and thereby also the pollution rises. The figure could describe the greenhouse gas situation over the last decades, and it could also describe the case of plastic pollution, where 2022 is different places on the *x*-axis dependent on the pollutant. The content in the international agreements, and thereby the national regulations and initiatives, and ultimately systemic change or not would define whether conceptual scenario A, B or C would be possible. Figure: Cyvin and Hellevik, 2023.

targeting the tail-end rather than the source of the problem (Riechers et al., 2021). Scientists should express themselves clearly and confidently when they find indications of severe effects of plastics, they should share their extrapolation exercise from small-scale impacts to ecosystem or even planetary level, and they should demand clear systemic changes when their results demand them. Some researchers might find this as out of their domain, but it can be done without compromising our research ethics boundaries if our recommendations are research based, and driven by evidence, not feelings. Maybe it is also time to tailor national and European research grants towards the systemic level, and its implementation into society? More research is of course needed, but that is, based on current knowledge about global severity, an absolute given.

In Figure 1, we broadly conceptualise the dynamic of push-and-pull between researchers, policymakers, time elapsing during these processes, meanwhile the pollution levels rise. We could place different pollutants or environmental issues into the conceptual model. The current possibility of reaching an early decline in the level of pollution (scenario C), might be overdue for plastic as a contaminant, but maybe we can reach scenario B instead of A if we manage to work together as an international community of researchers, NGOs, policymakers, and industries.

The pattern we are currently witnessing seems to lead towards scenario A in Figure 1. Decision makers call for more science, better information, better infrastructure to deal with the waste, discussions about which countries are responsible for the most plastic pollution and where it occurs. UNEP have, to frame it simply, achieved an international agreement about creating an international agreement (UNEP, 2022). The latter was demanded by Borelle et al. (2017) and before that by Rochman et al. (2013). But so far, there is limited content to be read in this agreement. It is, indeed, a paper with great possibilities, but so far, the paper is quite empty and without specific text or value.

Historic success can be repeated

Plastic is not the one and only environmental threat, but it is one very visible result of a long-term systemic failure. The Montreal Protocol is a great success story showing the power of collective action, which resulted in banning CFCs and halting the depletion of our ozone Layer.

Our concluding statement is that the research front now presents plastic as globally ubiquitous in nature and in humans' direct environment. Effects have been shown locally, and hypothesised plausibly on global biogeochemical cycles. This, combined with predictions of ever-increasing production and pollution is disturbing and should make us question the goals and intent of our economic/political system. Marine plastic pollution should, in terms of severity and policy priority be treated as the ozone layer depletion was. There are huge differences between these two environmental issues, but we can be inspired by the Montreal protocol from 1987. Let us together tackle and overcome (Figure 1 leading to scenario C) the issue as a global community of researchers, policymakers, industry,

and civil society; this is also possible now. As researchers, journal editors and reviewers, we must be bold in our communication of results and policy recommendations while maintaining our academic integrity. Meanwhile, policymakers and civil society must take our findings on board and prioritise issues threatening nature and societies. We cannot play out multiple grand experiments with our health and nature (Andrady and Neal, 2009, Wright and Kelly, 2017).

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

JBC and CH have shared all aspects of the publication process, from sketching to conceptualization, data analysis and writing of final manuscript as well as editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Ageel, H. K., Harrad, S., and Abdallah, M. A.-E. (2022). Occurrence, human exposure, and risk of microplastics in the indoor environment. *Environ. Sci. Process. Impacts* 24 (1), 17–31. doi:10.1039/D1EM00301A

Andrady, A. L., and Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Trans. R. Soc. B Biol. Sci.* 364 (1526), 1977–1984. doi:10.1098/rstb.2008.0304

Arp, H. P. H., Kühnel, D., Rummel, C., MacLeod, M., Potthoff, A., Reichelt, S., et al. (2021). Weathering plastics as a planetary boundary threat: Exposure, fate, and hazards. *Environ. Sci. Technol.* 55 (11), 7246–7255. doi:10.1021/acs.est.1c01512

Bastesen, E., Haave, M., Andersen, G. L., Velle, G., Bødtker, G., and Krafft, C. G. (2021). Rapid landscape changes in plastic bays along the Norwegian coastline. *Front. Mar. Sci.* 8, 579913. doi:10.3389/fmars.2021.579913

Bellasi, A., Binda, G., Pozzi, A., Boldrocchi, G., and Bettinetti, R. (2021). The extraction of microplastics from sediments: An overview of existing methods and the proposal of a new and green alternative. *Chemosphere* 278, 130357. doi:10.1016/j.chemosphere.2021.130357

Bonanno, G., and Orlando-Bonaca, M. (2020). Marine plastics: What risks and policies exist for seagrass ecosystems in the Plasticene? *Mar. Pollut. Bull.* 158, 111425. doi:10.1016/j.marpolbul.2020.111425

Borelle, S. B., Rochman, C. M., Liboiron, M., Bond, A. L., Lusher, A., Bradshaw, H., et al. (2017). Why we need an international agreement on marine plastic pollution. *Proc. Natl. Acad. Sci.* 114 (38), 9994–9997. doi:10.1073/pnas.1714450114

Chassignet, E. P., Xu, X., and Zavala-Romero, O. (2021). Tracking marine litter with a global ocean model: Where does it go? Where does it come from? *Front. Mar. Sci.* 8, 667591. doi:10.3389/fmars.2021.667591

Cyvin, J. B., Ervik, H., Kveberg, A. A., and Hellevik, C. (2021). Macroplastic in soil and peat. A case study from the remote islands of Mausund and Froan landscape conservation area, Norway; implications for coastal cleanups and biodiversity. *Sci. Total Environ.* 787, 147547. doi:10.1016/j.scitotenv.2021.147547

Danopoulos, E., Jenner, L. C., Twiddy, M., and Rotchell, J. M. (2020a). Microplastic contamination of seafood intended for human consumption: A systematic review and meta-analysis. *Environ. Health Perspect.* 128 (12), 126002. doi:10.1289/EHP7171

Danopoulos, E., Twiddy, M., and Rotchell, J. M. (2020b). Microplastic contamination of drinking water: A systematic review. *PLOS ONE* 15 (7), e0236838. doi:10.1371/journal.pone.0236838

Duncan, E. M., Davies, A., Brooks, A., Chowdhury, G. W., Godley, B. J., Jambeck, J., et al. (2020). Message in a bottle: Open source technology to track the movement of plastic pollution. *PLOS ONE* 15 (12), e0242459. doi:10.1371/journal.pone.0242459

European Commission. Joint Research Centre (2020). *A European threshold value and assessment method for macro litter on the coastlines*. Brussels, Belgium: European Commission.

Farmen, E., Provencher, J., Aliani, S., Baak, J., Bergmann, M., Booth, A. M., et al. (2021). *Litter and microplastics monitoring guidelines arctic monitoring & assessment programme*. https://www.amap.no/documents/download/6761/inline. doi:10.13140/RG.2.2.34524.72324

Frias, J. P. G. L., Pagter, E., Nash, R., O'Connor, I., Carretero, O., Filgueiras, A., et al. (2018). *Standardised protocol for monitoring microplastics in sediments*. P4 Deliverable D4.2 (Galway City, Mayo, Connemara: GMIT). doi:10.13140/RG.2.2.36256.89601/1

Galgani, L., and Loiselle, S. A. (2021). Plastic pollution impacts on marine carbon biogeochemistry. *Environ. Pollut.* 268, 115598. doi:10.1016/j.envpol.2020.115598

Henry, B., Laitala, K., and Klepp, I. G. (2019). Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment. *Sci. Total Environ.* 652, 483–494. doi:10.1016/j.scitotenv.2018.10.166

Hermsen, E., Mintenig, S. M., Besseling, E., and Koelmans, A. A. (2018). Quality criteria for the analysis of microplastic in biota samples: A critical review. *Environ. Sci. Technol.* 52 (18), 10230–10240. doi:10.1021/acs.est.8b01611

Huang, D., Xu, Y., Lei, F., Yu, X., Ouyang, Z., Chen, Y., et al. (2021). Degradation of polyethylene plastic in soil and effects on microbial community composition. *J. Hazard. Mater.* 416, 126173. doi:10.1016/j.jhazmat.2021.126173

Huserbråten, M. B. O., Hattermann, T., Broms, C., and Albretsen, J. (2022). Trans-polar drift-pathways of riverine European microplastic. *Sci. Rep.* 12 (1), 3016. doi:10.1038/s41598-022-07080-z

Jacquin, J., Cheng, J., Odobel, C., Pandin, C., Conan, P., Pujo-Pay, M., et al. (2019). Microbial ecotoxicology of marine plastic debris: A review on colonization and biodegradation by the "plastisphere". *Front. Microbiol.* 10, 865. doi:10.3389/fmicb.2019.00865

Jenner, L. C., Rotchell, J. M., Bennett, R. T., Cowen, M., Tentzeris, V., and Sadofsky, L. R. (2022). Detection of microplastics in human lung tissue using μFTIR spectroscopy. *Sci. Total Environ.* 831, 154907. doi:10.1016/j.scitotenv.2022.154907

Ji, Z., Huang, Y., Feng, Y., Johansen, A., Xue, J., Tremblay, L. A., et al. (2021). Effects of pristine microplastics and nanoplastics on soil invertebrates: A systematic review and meta-analysis of available data. *Sci. Total Environ.* 788, 147784. doi:10.1016/j.scitotenv.2021.147784

Joyce, H., Frias, J., Kavanagh, F., Lynch, R., Pagter, E., White, J., et al. (2022). Plastics, prawns, and patterns: Microplastic loadings in *Nephrops norvegicus* and surrounding habitat in the North East Atlantic. *Sci. Total Environ.* 826, 154036. doi:10.1016/j.scitotenv.2022.154036

Khalid, N., Aqeel, M., Noman, A., Hashem, M., Mostafa, Y. S., Alhaithloul, H. A. S., et al. (2021). Linking effects of microplastics to ecological impacts in marine environments. *Chemosphere* 264, 128541. doi:10.1016/j.chemosphere.2020.128541

Kim, S.-K., Lee, H.-J., Kim, J.-S., Kang, S.-H., Yang, E.-J., Cho, K.-H., et al. (2021). Importance of seasonal sea ice in the Western Arctic ocean to the Arctic and global microplastic budgets. *J. Hazard. Mater.* 418, 125971. doi:10.1016/j.jhazmat.2021.125971

Kirstein, I. V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., et al. (2016). Dangerous hitchhikers? Evidence for potentially pathogenic Vibrio spp. on microplastic particles. *Mar. Environ. Res.* 120, 1–8. doi:10.1016/j.marenvres.2016.07.004

Knutsen, H., Cyvin, J. B., Totland, C., Lilleeng, Ø., Wade, E. J., Castro, V., et al. (2020). Microplastic accumulation by tube-dwelling, suspension feeding polychaetes from the sediment surface: A case study from the Norwegian continental shelf. *Mar. Environ. Res.* 161, 105073. doi:10.1016/j.marenvres.2020.105073

Lee, J., and Chae, K.-J. (2021). A systematic protocol of microplastics analysis from their identification to quantification in water environment: A comprehensive review. *J. Hazard. Mater.* 403, 124049. doi:10.1016/j.jhazmat.2020.124049

Logemann, A., Reininghaus, M., Schmidt, M., Ebeling, A., Zimmermann, T., Wolschke, H., et al. (2022). Assessing the chemical anthropocene – development of the legacy pollution fingerprint in the North Sea during the last century. *Environ. Pollut.* 302, 119040. doi:10.1016/j.envpol.2022.119040

López-Martínez, S., Morales-Caselles, C., Kadar, J., and Rivas, M. L. (2020). Overview of global status of plastic presence in marine vertebrates. *Glob. Change Biol.* 27 (4), 728–737. doi:10.1111/gcb.15416

MacLeod, M., Arp, H. P. H., Tekman, M. B., and Jahnke, A. (2021). The global threat from plastic pollution. *Science* 373 (6550), 61–65. doi:10.1126/science.abg5433

Maga, D., Galafton, C., Blömer, J., Thonemann, N., Özdamar, A., and Bertling, J. (2022). Methodology to address potential impacts of plastic emissions in life cycle assessment. *Int. J. Life Cycle Assess.* 27 (3), 469–491. doi:10.1007/s11367-022-02040-1

Meadows, D. (1999). *Leverage points: Places to intervene in a system*. Hartland, WI: The Sustainability Institute.

Multisanti, C. R., Merola, C., Perugini, M., Aliko, V., and Faggio, C. (2022). Sentinel species selection for monitoring microplastic pollution: A review on one health approach. *Ecol. Indic.* 145, 109587. doi:10.1016/j.ecolind.2022.109587

Nematollahi, M. J., Zarei, F., Keshavarzi, B., Zarei, M., Moore, F., Busquets, R., et al. (2022). Microplastic occurrence in settled indoor dust in schools. *Sci. Total Environ.* 807, 150984. doi:10.1016/j.scitotenv.2021.150984

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 56 (3), 1510–1521. doi:10.1021/acs.est.1c04158

Pirsaheb, M., Hossini, H., and Makhdoumi, P. (2020). Review of microplastic occurrence and toxicological effects in marine environment: Experimental evidence of inflammation. *Process Saf. Environ. Prot.* 142, 1–14. doi:10.1016/j.psep.2020.05.050

Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., and Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Sci. Total Environ.* 702, 134455. doi:10.1016/j.scitotenv.2019.134455

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., et al. (2021). Plasticenta: First evidence of microplastics in human placenta. *Environ. Int.* 146, 106274. doi:10.1016/j.envint.2020.106274

Riechers, M., Brunner, B. P., Dajka, J.-C., Duşe, I. A., Lübker, H. M., Manlosa, A. O., et al. (2021). Leverage points for addressing marine and coastal pollution: A review. *Mar. Pollut. Bull.* 167, 112263. doi:10.1016/j.marpolbul.2021.112263

Rillig, M. C., Leifheit, E., and Lehmann, J. (2021). Microplastic effects on carbon cycling processes in soils. *PLOS Biol.* 19 (3), e3001130. doi:10.1371/journal.pbio.3001130

Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., Hoh, E., Karapanagioti, H. K., et al. (2013). Classify plastic waste as hazardous. *Nature* 494 (7436), 169–171. doi:10.1038/494169a

Ryan, P. G. (2015). "A brief history of marine litter research," in *Marine anthropogenic litter*. Editor I. M. Bergmann, L. Gutow, and M. Klages (Springer International Publishing), 1–25. doi:10.1007/978-3-319-16510-3_1

Sharifinia, M., Bahmanbeigloo, Z. A., Keshavarzifard, M., Khanjani, M. H., and Lyons, B. P. (2020). Microplastic pollution as a grand challenge in marine research: A closer look at their adverse impacts on the immune and reproductive systems. *Ecotoxicol. Environ. Saf.* 204, 111109. doi:10.1016/j.ecoenv.2020.111109

Sönmez, V. Z., Akarsu, C., and Sivri, N. (2022). "The ecotoxicological effects of microplastics on trophic levels of aquatic ecosystems," in *Microplastic pollution*. Editor I. M. Z. Hashmi (Springer International Publishing), 389–428. doi:10.1007/978-3-030-89220-3_18

Sripada, K., Wierzbicka, A., Abass, K., Grimalt, J. O., Erbe, A., Röllin, H. B., et al. (2022). A children's health perspective on nano- and microplastics. *Environ. Health Perspect.* 130 (1), 015001. doi:10.1289/EHP9086

Steer, M., Thompson, R. C., Streit-Bianchi, I. M., Cimadevila, M., and Trettnak, W. (2020). "Plastics and microplastics: Impacts in the marine environment," in *Mare plasticum—the plastic sea* (Berlin, Germany: Springer International Publishing). doi:10.1007/978-3-030-38945-1_3

Strand, K. O., Huserbråten, M., Dagestad, K.-F., Mauritzen, C., Grøsvik, B. E., Nogueira, L. A., et al. (2021). Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic. *Sci. Total Environ.* 790, 148009. doi:10.1016/j.scitotenv.2021.148009

Tsangaris, C., Panti, C., Compa, M., Pedà, C., Digka, N., Baini, M., et al. (2021). Interlaboratory comparison of microplastic extraction methods from marine biota tissues: A harmonization exercise of the plastic busters MPAs project. *Mar. Pollut. Bull.* 164, 111992. doi:10.1016/j.marpolbul.2021.111992

United Nations Environment Assembly Programme (Unep) (2022). End plastic pollution: Towards an international legally binding instrument (EA.5/Res.14). https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/39764/END%20PLASTIC%20POLLUTION%20-%20TOWARDS%20AN%20INTERNATIONAL%20LEGALLY%20BINDING%20INSTRUMENT%20-%20English.pdf?sequence=1&isAllowed=y.

Villarrubia-Gómez, P., Cornell, S. E., and Fabres, J. (2018). Marine plastic pollution as a planetary boundary threat – the drifting piece in the sustainability puzzle. *Mar. Policy* 96, 213–220. doi:10.1016/j.marpol.2017.11.035

Watson-Wright, W. M. (2005). "Policy and science: different roles in the pursuit of solutions to common problems," in *Politics and socio-economics of ecosystem-based management of marine resources*. Editor H. I. Browman and K. I. Stergiou (Marine Ecology Progress Series) 300, 291–296.

Wagner, M., and Bank, I. M. S. (2022). "Solutions to plastic pollution: A conceptual framework to tackle a wicked problem," in *Microplastic in the environment: Pattern and process* (Berlin, Germany: Springer International Publishing). doi:10.1007/978-3-030-78627-4_11

Wang, F., Feng, X., Liu, Y., Adams, C. A., Sun, Y., and Zhang, S. (2022). Micro(nano) plastics and terrestrial plants: Up-to-date knowledge on uptake, translocation, and phytotoxicity. *Resour. Conservation Recycl.* 185, 106503. doi:10.1016/j.resconrec.2022.106503

World Health Organisation (WHO) (2021). *Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health*. Geneva: World Health Organization. Available at: https://www.who.int/publications/i/item/9789240054608

Woods, J. S., Verones, F., Jolliet, O., Vázquez-Rowe, I., and Boulay, A.-M. (2021). A framework for the assessment of marine litter impacts in life cycle impact assessment. *Ecol. Indic.* 129, 107918. doi:10.1016/j.ecolind.2021.107918

Wright, S. L., and Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environ. Sci. Technol.* 51 (12), 6634–6647. doi:10.1021/acs.est.7b00423

Zhang, B., Yang, X., Chen, L., Chao, J., Teng, J., and Wang, Q. (2020). Microplastics in soils: A review of possible sources, analytical methods and ecological impacts. *J. Chem. Technol. Biotechnol.* 95 (8), 2052–2068. doi:10.1002/jctb.6334