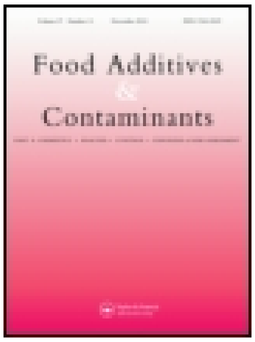

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Managing the analytical challenges related to micro- and nanoplastics in the environment and food: filling the knowledge gaps

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ABSTRACT
This paper identifies knowledge gaps on the sustainability and impacts of plastics and presents some recommendations from an expert group that met at a special seminar organised by the European Commission at the end of 2018. The benefits of plastics in society are unquestionable, but there is an urgent need to better manage their value chain. The recently adopted European Strategy for Plastics stressed the need to tackle the challenges related to plastics with a focus on plastic litter including microplastics. Microplastics have been detected mainly in the marine environment, but also in freshwater, soil and air. Based on today's knowledge they may also be present in food products. Although nanoplastics have not yet been detected, it can be assumed that they are also present in the environment. This emerging issue presents challenges to better understand future research needs and the appropriate immediate actions to be taken to support the necessary societal and policy initiatives. It has become increasingly apparent that a broad and systematic approach is required to achieve sustainable actions and solutions along the entire supply chain. It is recognised that there is a pressing need for the monitoring of the environment and food globally. However, despite the number of research projects increasing, there is still a lack of suitable and validated analytical methods for detection and quantification of micro- and nanoplastics. There is also a lack of hazard and fate data which would allow for their risk assessment. Some priorities are identified in this paper to bridge the knowledge gaps for appropriate management of these challenges. At the same time it is acknowledged that there is a great complexity in the challenges that need to be tackled before a really comprehensive environmental assessment of plastics, covering their entire life cycle, will be possible.

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Introduction

Although plastic materials play an essential role in our modern society, it is now well understood, especially due to increasing public debate, that there is an urgent need for better management of their value chain and for understanding of their impact on the environment and human wellbeing. Plastics improve the daily lives of citizens, and given all their functionalities, there is no way to ban them from society. At the same time, negative impacts related to their end-of-life including a better understanding of potential leaching of chemicals during their use phase need to be tackled urgently. The Marine Strategic Framework Directive (MSFD) requires that EU Member States ensure that marine litter, including plastic litter, does not cause harm to the coastal and marine environment (European Commission 2008). An iterative process of monitoring, assessment and implementation of measures has therefore been set-up. The European Strategy for Plastics in a Circular Economy (European Commission 2018a) stresses the need to tackle the challenges related to plastics, with the latter being identified as one of the five priority areas addressed in the EU Action Plan for the Circular Economy (European Commission 2015). Moreover, the European Commission confirmed in 2017 that it would focus on the production and use of plastics with the intention to ensure that all plastic packaging is recyclable by 2030 (European Commission 2017). The key challenges to the

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entire life-cycle of plastics include the use of fossil resources as feedstock, current low re-use and recycling rates, coupled with high incineration and landfilling levels, and the littering of plastics that end up in the terrestrial and marine environments caused by improper waste management. The increasing amount of plastic waste with millions of tons ending up in the oceans (Jambeck et al. 2015) and in particular of 'single-use' plastic products such as packaging materials, shopping bags, and disposable tableware is of particular concern (European Commission 2008), even if precise figures on the amount are hard to estimate and even harder to verify. For instance, it is estimated that in the EU alone, 150,000 to 500,000 tons of plastic waste make their way into the oceans every year (Sherrington et al. 2016). Although this may only represent a relatively small proportion of global marine litter, certain areas are heavily affected. For instance, it has been demonstrated that the density of accumulation in the Mediterranean is the highest globally, caused by about 700 tons of plastic waste entering the Mediterranean every day (Galgani et al. 2015). This pollution by plastics is not only detrimental to the environment, but also causes economic damage to tourism and fisheries (Werner et al. 2016). In order to address major plastic littering and pollution issues, the recently adopted new EU Directive on Single-Use Plastics (European Commission 2018b) lays out rules which will ban the use of certain throwaway plastic products for which suitable alternatives exist such as plastic straws, cotton swabs, disposable plastic plates and cutlery by 2021. Moreover, specific measures will be introduced to reduce the likelihood that some of the most frequently littered plastic products will keep entering the environment in an uncontrolled way, e.g. 90% of plastic bottles will have to be collected by 2025.

In addition to direct littering of plastics, their degradation due to physical stress from the environment such as abrasion, as in the case of e.g. tyres or synthetic clothes being washed and exposure to ultraviolet radiation can trigger the occurrence of very small fragments, the so called microplastics (MPs). These are known as 'secondary' MPs, whereas also 'primary' MPs such as plastic powder, paints and coatings used by industry or microbeads present in cosmetics, detergents and other domestic products used by consumers can be directly released into the environment (Cole et al. 2011; Boucher and Friot 2017; GESAMP 2019). To overcome the ambiguous terminology for MPs, a definition and categorisation framework has been proposed recently to support progress in research and mitigation measures (Hartmann et al. 2019).

MPs have not only been found in the sea, where they can accumulate in particular in the sediment, but potentially also in the water column, and also present in the air, water including drinking water and the food chain. Although there is no universally agreed definition of MPs (synthetic polymer particles), most studies refer to particles with a diameter size of less than 5 mm; some indicate smaller sizes of 50 µm or even 10 nm, with the latter belonging to the category of nanoplastics (Law and Johnson 2014; Verschoor 2015; GESAMP 2019; SAPEA 2019; Hartmann et al. 2019). There is a huge variation related to the estimates of MP emissions into the environment, most probably caused by the wide variety of terminologies, i.e. definitions used but also by the absence of reliable exposure data, various modelling methodologies and differences in assumptions and approximations made by researchers. (Hann et al. 2018). Moreover, to-date, there is some albeit scarce information on the possible occurrence of nanoplastics in the environment and food chain. In the EU, micro-litter, including MPs, is considered under the MSFD (European Commission 2008), guidance for the monitoring of micro-litter is provided through the MSFD Technical Group on marine litter.

The European Commission's Scientific Advice Mechanism (SAM) was tasked by the European Commission in 2018 to deliver science-based policy advice on the health and environmental impacts of MPs. SAM is supported by the EU's Horizon 2020 Programme funded consortium SAPEA (Science Advice for Policy by European Academies) which, in January 2019 published a dedicated report on the scientific perspective on MPs in nature and society based on the best available evidence (SAPEA 2019) with the following conclusion as stated in the report: " *While ecological risks are very rare at present for NMPs*[1] *(plastics of sizes below 5mm), there are at least some locations in coastal waters and sediments where ecological risks might currently exist. If future emissions to the environment remain constant, or increase, the ecological risks may be widespread within a century. Little is known with respect to the human health risks of NMPs, and what is known is surrounded by considerable uncertainty; however, the relevant conclusion of this working group is that we have no evidence of widespread risk to human health from NMPs at present"*. From this report, it can be concluded that there is currently no evidence pointing at a widespread risk.

In order to carry out appropriate risk assessment, adequate eco-toxicological methods for hazard identification as well as analytical methods for the detection and quantification of NMPs are needed to determine the exposure levels in the environment and food chain. However, it is important to note that there is a huge variety of NMPs, not only in their particle size but also in chemical composition, which poses a considerable challenge to risk assessors. There are many uncertainties in determining whether 'classical' risk assessment approaches are sufficient, mainly because of long-term accumulation and exposure (EFSA 2016; ECHA 2019). Moreover, similarly to the risk assessment of nanomaterials (ECHA 2017), 'classical' risk assessment is designed for dissolved chemicals and not for particulate matters. In this respect it should be stressed that the classical exposure vs hazard assessment applies; however, the tools to assess these will be likely to be different for NMPs compared to chemicals.

In reviewing the scientific literature and various reports, it becomes apparent that there is an urgent need for more knowledge, especially on realistic figures, i.e. accurate estimates related to the amount of NMPs, their fate, their exposure to humans (e.g. via the food chain) and the environment and the effects that might be caused.

In November 2018 the European Commission's Joint Research Centre (JRC) organised a special seminar on the sustainability and impacts of plastics, with the aim to discuss the main issues and challenges to allow for a better understanding of the research needs that should support societal and policy initiatives in the future. The event brought together high-level representatives from the European Commission and experts covering different stages in the life cycle of plastics. This paper provides a summary of the topics discussed at the seminar. It outlines policy needs, stakeholders' opinions and the research gaps to be filled to support risk assessment bodies and policy makers for a better understanding and handling of the issue of plastics, including NMPs. Moreover, it also presents proposals for immediate actions to be taken.

Challenges to stakeholders

The challenges are significant due to the generation of around 27 million tons of plastic waste annually in the EU, of which in 2016 only about 8.4 million tons were recycled of which one third was exported outside Europe (Plastics Europe 2018). Of those, only about 3.5 million tons of recycled plastics entered into European products. While the 'use phase' of plastics brings a variety of benefits to the users, there is a need for better handling the end-of-life of plastics but also potential losses during their handling and use. This includes MP emissions during e.g. fibre shedding (Almroth et al. 2018) or pellet losses (Karlsson et al. 2018). Moreover, it is important to better understand possible leaching of chemicals during the use phase of plastics and their end-of-life. To understand the overall picture of the benefits and burdens of the use of plastic as e.g. packaging material, it is important also to include the life cycle assessment of packaged products rather than concentrating on the packaging material alone. Moreover, there is a need to distinguish between short-lived products and long-lasting products. Bio-based and biodegradable plastics are considered by some stakeholders as a major solution for sustainable plastics in a circular economy context. When biodegradable plastics are used it is important to have standards in place to ensure biodegradability under various environmental conditions on top of biodegradability in industrial composting facilities. Today, based on the current collection, sorting and recycling technologies, it is not possible to achieve 100% recycling of plastics (Vangheluwe 2018). Consequently, it is necessary to accelerate the development and implementation of a meaningful strategic research and innovation agenda. Speeding up innovation and industry collaboration along the entire value chain is paramount in this respect, given that the ambitious European Plastics Strategy provides plastic producers with a challenging opportunity that should appropriately be explored (Vangheluwe 2018). The Plastics Strategic Research & Innovation Agenda in a Circular Economy provides already a good vehicle for this (SUSCHEM 2019). The voluntary commitment by the plastics industry encompasses ambitious targets (Global Plastics Alliance 2011; Operation Clean Sweep 2019) such as:

- Increased engagement inside and outside of the industry;
- Accelerated innovation in the full life cycle of products;
- Reaching 100 % re-use, recycling and/or recovery of all plastic packaging by 2040, with 60 % already by 2030;
- Preventing the leakage of plastics into the environment.

Members of the plastics value chain also made significant voluntary pledges regarding increased recycling of plastics and the use of recycled material as input for production in the EU (European Commission 2019). European initiatives such as SusChem – the European Technology Platform for Sustainable Chemistry, bringing together industry, academia, policy makers and the wider society to initiate and inspire European chemical and biochemical innovation with the aim to provide sustainable solutions, are seen as important to speed up innovation.

Views from plastic recyclers

As more plastics were produced in the last decade than in the entire 20th century, this eventually generated enormous amounts of plastic waste. Since 1950, more than 8.7 billion tons of plastic have been manufactured with the cumulative production estimated to hit 34 billion tons by 2050 (Emans 2018; Beckman 2018). The plastic recycling industries have welcomed the European Strategy for Plastics as being a promising transition. As a positive outcome, it is worth noting that since the adoption of the Circular Economy Strategy, the recycling of polyethylene films has increased by more than 30%, thanks to the growing investments in recycling technologies by many companies (Emans 2018). Suffice to say that not only the plastic recycling industry is required to take appropriate actions, but also plastics producers and users, including end-consumers. All waste plastic materials need to be collected and properly sorted to create valuable plastic waste and to avoid littering of land and oceans. It should be noted that high levels of plastic waste contamination render their collection, sorting and recycling expensive. In this respect, it must be stressed that only easily recyclable products can be recycled economically. A product is recyclable under several conditions:

- The product must be made of a plastic that is collected for recycling;
- The recycled product has market value and/or is supported by a legislatively mandated programme;
- The product must be sorted and aggregated into defined streams for recycling processes;
- The product can be processed and reclaimed/recycled with commercial recycling processes (e.g. Extended Producer Responsibility schemes);
- The recycled plastic becomes a raw material to be used in the production of new products.

However, there is an urgent need to equate supply and demand. Currently, it is still difficult for recycled plastic materials to compete with virgin materials. One of the reasons is that whilst there is no international harmonisation in terms of authorisation and use of additives the recycling industry lacks full information on the additives currently used by plastic producers. Especially challenging is the recycling of mixed and multi-layered plastics. Biodegradable plastics cause another challenge if they contaminate 'conventional' plastic waste, as they can deteriorate the quality of the recycled materials. However, it is the quality, which is a key factor for recycled materials, which consequently will add value to the economy. There is a strong wish for harmonisation of quality standards regarding the outlet of sorting centres in Europe, with a particular focus on the quality and quantity. Inefficient collection and sorting make recycling expensive, thus posing a big hurdle to plastics recyclers who are mostly small and medium size enterprises (SMEs). If the future work on recycling is done properly, economic benefits can be expected together with the creation of a significant number of jobs.

Researchers' needs and expectations

Recent research studies on marine litter reveal the existence of several misconceptions. At the same time, many trends and impacts are still unknown, especially in the case of small sized particles. There is an urgent need for research to be appropriately translated into a policy making process. Research priorities should focus on NMPs to get a better understanding of all processes related to the generation, fate, exposure, and effects of those plastics. Recent literature reviews confirmed the presence of MPs in surface water and sediments as well in some (limited) food products (Burns and Boxall 2018; Toussaint et al. 2019; Hantoro et al. 2019; Koelmans et al. 2019 and papers cited herein). Detection and quantification of NMPs in complex matrices such as food products is difficult, primarily due to the absence of reliable analytical methods (Hermsen et al. 2018). This explains the relatively scarce information on contamination levels in the food chain. A further challenge is to understand the physicochemical properties of MPs which are extremely heterogeneous and pose a significant challenge in making appropriate toxicological assessments (Lambert et al. 2017).

Therefore, there is a need to optimise the sampling efforts, to have automated sensors and real time measurements at hand as a way towards a better understanding the potential harm from exposure to small plastic particles. The quantitative fluxes of macro- and microplastics are still unknown, as the topic is highly complex.

As there is a complex interaction between the scales of local plastic sources in the environment with rampant changing environmental conditions, the distribution of MPs in the environment is highly heterogeneous (Welden and Lusher 2017).

A recent study that reviewed the weight of evidence of MPs that cause environmental harm concluded that although MPs are found specifically in the aquatic environment, the concentrations detected nowadays would be orders of magnitude lower than those reported to affect ecotoxicological endpoints (Burns and Boxall 2018). Moreover, there is also not so much evidence that MPs can act as a vector for hydrophobic organic compounds to accumulate in organisms (Koelmans et al. 2016; Diepens and Koelmans 2018). However, there is still a discrepancy between the particle types, size ranges and concentrations in the tests carried out in the laboratory and those that are found in nature (Kwon et al. 2017; Hartmann et al. 2017; Burns and Boxall 2018). Therefore, there is an urgent need for quality assurance of data achieved keeping in mind realistic exposure assessments. This includes quantifying the uptake and depuration rates in organisms at different trophic levels and quantifying the influence that MPs have on the uptake of environmental contaminants (Au et al. 2017). However, at hot-spot locations (coastal areas and highly polluted rivers) environmental concentrations may reach levels that might affect negatively sensitive aquatic organisms (Besseling et al. 2019). Furthermore, simulation of future concentrations of MPs indicates an increase (Koelmans et al. 2017), therefore the fraction of sites 'at risk' will increase over time.

The inputs of MP from the atmosphere may also be more important than issues related to marine litter, which needs to be further explored. Moreover, concerning the impact on human health, it is also important to understand the MP exposure through food and drinking water consumption (Koelmans et al. 2019). Although numerous scientific studies confirm that the highest quantities of MPs are in the digestive tract of seafood, which is a part of commercial fish that is usually discarded before consumption, there is still little knowledge about NMPs in other food products (Toussaint et al. 2019). The European Food Safety Authority concluded that there is an urgent need for occurrence data in food and moreover to understand the effects of food processing (EFSA 2016). In addition to the requirements for toxicological studies as described above, EFSA requested research on the toxicokinetics, in particular on local effects in the gastrointestinal (GI) tract, as MPs may degrade in the GI by forming nanoparticles.

Although there are already a considerable number of identification methods available (Hidalgo-Ruz et al. 2012; Huppertsberg and Knepper 2018; Toussaint et al. 2019), there is still an absence of methods for quantification of MPs to understand their occurrence in drinking water and food. The analysis of nanoparticles is even more challenging. It is important to stress that reliable exposure data should be based on the use of validated analytical methods, not only concerning the detection and quantification part, but also for sampling and sample preparation (Hermsen et al. 2018; Koelmans et al. 2019).

From a more comprehensive point-of-view, there are considerable knowledge gaps to be addressed before a robust assessment of the potential environmental and human health impacts can be conducted in product related assessments such as life cycle assessments or environmental footprints:

- The share of plastics, which end up as litter in the environment, needs to be determined on a product specific level;
- The degradation/fragmentation of macroplastics to NMPs needs to be assessed (or is it reasonable to assume as worst case assumption that 100% of littered macroplastics will eventually become MP and NP?);
- Fate, exposure and effect values for different NMPs under varying environmental conditions need to be determined. Moreover, the underpinning toxicological data need to be quality assured.

Without this kind of information, it will be very difficult, if not impossible, to assess how "big" the issues of littering macroplastics, of NMPs are, compared to other environmental and human health challenges that the society faces. These conclusions are very much in line with the research needs identified in a recent report of the World Health Organisation (WHO 2019).

Regulatory needs and actions

Although the invention of plastics can be seen as a real success in satisfying the needs of modern society, some of its adverse impacts have somewhat been neglected, hence leading to threats to the environment and therefore posing a societal challenge. Currently some 27 million tons of plastic waste are generated in the EU every year, but only around 30% are recycled (Plastics Europe 2018). Globally, only about 15 % of plastic waste is collected for recycling with the majority ending up in a landfill or the environment, e.g. in the oceans. Globally, based on low collection rates for recycling of 14%, and additional value losses during the recycling process, according to estimates, 95 % of the value of plastic packaging material, i.e. between EUR 70 and 105 billion annually, is lost to the economy after a very short first-use cycle (Ellen MacArthur Foundation 2016). Consequently, the European Plastics Strategy has set a number of ambitious goals for which Europe is perceived as a leader at a global level. The strategy is based on four main pillars:

- Improving the economics and quality of plastics recycling;
- Curbing plastic waste and littering;
- Driving innovation and investment towards circular solutions;
- Harnessing global action.

There is a pressing need for regulatory measures, including those aiming at the issue of MPs, greater transparency on additives in plastics, increased use of oxo-degradable plastics, and the improvement of circularity. This includes a review of the waste legislation aimed at reducing land-filling; the regulation of single-use plastics which represent the largest share of all marine litter; possible restrictions of primary, intentionally added MPs; and appropriate labelling measures to raise awareness among consumers. The latter is important to improve the quality of waste collections. It is also important to understand the impact of an increased use of oxo-degradable plastics, as these represent a significant source of MPs. Oxo-degradable plastics are usually polyolefins, mainly polyethylene, and by oxo-degradation, compact plastics are transferred into very small particles. In this respect, the European Commission has recommended EU-wide measures to be taken in this respect (European Commission 2018d).

To identify appropriate solutions to the complex problems, many issues need to be broadly discussed with all stakeholders. All measures need to be based on sound scientific facts and robust life-cycle and risk assessments. Given that by 2030 every plastic packaging material placed on the EU market will either be reusable or can be recycled in a cost-effective manner, several steps need to be taken to make the life cycle of plastics as sustainable as possible. Concerning the waste collection, a harmonised collection system for plastic packaging waste within the EU and appropriate standards are seen as necessary to boost recycling quantity and quality. Legislation making the use of recycled products mandatory is seen by some stakeholders as an important step forward. However, it is important to issue appropriate specifications per product and its application. Policy makers need to reach out to industries by pushing for innovation and facilitating regulatory acceptance of new materials. In that respect, the European Commission pledging exercise offers a good opportunity to increase the voluntary uptake of recycled plastics into European products.

In the absence of robust data to understand the exposure of NMPs to humans and the environment and consequently the risks, some researchers have suggested that stakeholders should discuss possible and provisional action levels for MPs in seafood (Hantoro et al. 2019).

Conclusions and outlook

The strong European commitment towards the protection of the marine environment, better life cycle assessment and management of plastics through the enactment of the European Plastics Strategy, the call for plastic free seas and oceans in the updated Bioeconomy Strategy (European Commission 2018c), and research projects funded by the European Commission should be exploited. In keeping the global challenges in mind, there is a need for a worldwide focus on waste management and the export of European waste management expertise. Moreover, recycling operations should move to value creation instead of only waste management. Therefore, the recycling sector needs legal certainties and clear definitions to create a level playing field.

It is evident that for many aspects a stronger evidence base is necessary for better informed decisions in policy and business by:

- An increase in transparency on the flows of plastics from the EU, extending to the environmental and social conditions under which they are actually recycled, especially in developing economies;
- An increase in transparency on the substances used in plastics, including additives;
- More comprehensive assessments of proposed solutions to avoid overlooking relevant aspects and creating 'solutions' that may be regretted at a later stage;
- An increase in cooperation not only along the entire plastics value chain but also with stakeholders in academia and regulators at various levels (EU, Member States, Regions).

Regarding the urgent need to understand the realistic exposure to humans and the environment from NMPs and the related risks, it can be concluded that substantial scientific efforts are currently imminent. However, the largest challenge for risk assessment is the availability of robust data to understand the extent of exposure to humans and the environment and resulting effects. Whereas there is no doubt about the presence of MPs in coastal areas and subsequently fish worldwide, however, there is presently no robust risk-based approach available to assess potential impacts on humans and the environment. Based on the outcome of recent discussions in various scientific fora, it can be concluded that, presently, it is not possible to assess the full picture of human exposure to NMPs. This is because of the lack of harmonised and validated analytical methods (and reference materials) and also due to the shortfall of standardised reporting, especially given the absence of internationally accepted definitions.

It is of utmost importance to harmonise the nomenclature related to the characterisation of plastic debris, especially having a stringent definition in terms of their size classification to avoid confusion (Hartmann et al. 2019).

Therefore, there is a pressing need for the monitoring of environmental and food samples at the European level, ideally globally, and the appropriate data management should be promoted and harmonised. To get a better understanding of the occurrence of MPs in the environment, initiatives involving citizens in collecting beach samples as carried out recently in the Netherlands may be a good approach when enlarging it to a global scale (Bosker et al. 2017) however, this may have strong limitations as well (Breit 2017).

It is of utmost importance to gather the NMPs measurement communities together to discuss the most appropriate analytical approaches and their robustness. The most prominent topic (matrix) is water in terms of surface water representing seas, tap water and bottled water making an important part of the food chain. The JRC, in its role as the European Commission's in-house science and knowledge service, is planning to set up, amongst other actions, a European Network of Laboratory Analysts capable of measuring NMPs. This network shall comprise experts from all sectors of society (official control, industry, private laboratories) and its objectives will be:

- To discuss the currently commonly used definition of NMPs and determine the particle scale to investigate further;
- To identify the most suitable analytical approaches for the detection and quantification of NMPs in water, food and other consumer products;
- To test the robustness of selected analytical methods through e.g. proficiency tests;
- To validate the most suitable analytical approaches;
- To discuss and prioritise the need for reference materials.

The JRC has already started the production of reference materials and the organisation of proficiency tests for those laboratories willing to participate. Moreover, the JRC is planning to establish and maintain a MP and NP repository, i.e. a collection of materials that can be used for quality control purposes for monitoring and risk assessment.

In the next step, the JRC, in close collaboration with European Agencies such as ECHA and EFSA, will invite experts related to risk assessment of NMPs to discuss the challenges and the most suitable assessment methodologies and related data requirements for the assessment of fate, exposure, and effects. Once those methods and data are better understood and available, it will be also possible to include an assessment of potential environmental impacts of plastic littering, of NMPs in comprehensive product related assessment schemes.

Note

1. The term NMPs is representing both, nano- and microplastics.

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