Trends in Analytical Chemistry 165 (2023) 117142

Contents lists available at ScienceDirect

Trends in Analytical Chemistry

journal homepage: www.elsevier.com/locate/trac

Towards a rational and efficient risk assessment for microplastics

Albert A. Koelmans [a, *], Berte M. Gebreyohanes Belay [a, c], Svenja M. Mintenig [a], Nur Hazimah Mohamed Nor [b], Paula E. Redondo-Hasselerharm [d], Vera N. de Ruijter [a]

[a] Aquatic Ecology and Water Quality Management Group, Wageningen University & Research, the Netherlands
[b] Asian School of the Environment, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[c] Department of Aquatic Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Droevendaalsesteeg 10, Wageningen, 6708 PB, the Netherlands
[d] IMDEA Water Institute, Science and Technology Campus of the University of Alcalá, Avenida Punto Com, 2, 28805, Alcalá de Henares, Madrid, Spain

ARTICLE INFO

Article history:
Received 10 March 2023
Received in revised form
31 May 2023
Accepted 14 June 2023
Available online 21 June 2023

Keywords:
Microplastic
Probability density functions
Vector effect
Exposure assessment
Effect assessment
Risk assessment
Risk management

ABSTRACT

To avoid confusion about the risks of microplastics in the public domain, it is crucial that differences in terminology and approach within existing risk assessment frameworks are clear to risk managers. In this article, we discuss key concepts and recent literature on the risk assessment of microplastics and provide a shortlist of crucial elements to consider. Furthermore, we compare and contrast two approaches that have been published but have not yet been compared in detail. One method uses categories of particle properties, does not include an impact assessment, and is limited to the risk of particles in a sample. The other method uses continuums of particle properties, incorporates biological properties into an impact assessment, and focuses on the risk of all particles in the system. We discuss both approaches in light of existing disciplinary scientific knowledge, risk assessment science, and their relevance to risk managers.

1. Introduction

Scientists have made good progress in recent years in developing risk assessment frameworks for microplastic particles [1–4]. Prospective risk assessment of microplastic particles is important for determining when and where risks can be expected for ecosystems and humans. This information forms the basis for regulations and the design, prioritization, and timing of solutions. However, risk assessment for microplastic particles is complex and uncertain, as described in recent literature. This complexity, as well as inconsistencies in terminology, can easily lead to misinterpretations and confusion about how published risk assessment methods work. Such misinterpretations can then lead to delays in the implementation of risk assessment methods in risk management. Since plastic pollution is an urgent problem, such delays are undesirable, even if they are, to some extent, inevitable and understandable. Therefore, in our opinion, it is important to identify crucial components for the quality of risk assessment frameworks and to discuss the differences in existing approaches and schools of thought in the scientific literature in light of such quality criteria, to develop our science efficiently.

Previously, we contributed to the development of risk assessment frameworks specifically designed for use by regulators [1,3,5,6]. A distinguishing feature of that framework is that it uses probability density functions (PDFs) that allow the entire microplastic continuum to be taken into account with minimal information loss (PDF framework). Since then, a second framework has been published by Bucci and Rochman (BR framework) [7] with the following motivation: "*Some groups have developed risk assessment frameworks that simplify the dimensions of microplastics by aligning all particles in a sample to a standardized shape and size range* [3,4,8]. *In this paper, we aim to develop a framework that maintains the complexity of microplastics by capturing the hazard associated with both their physical and chemical characteristics to assess risk*." It is thus suggested that the BR framework maintains the complexity of microplastics and does not simplify the properties or simplify them less compared to the PDF framework. However, a detailed comparison and discussion of the two approaches are so far lacking. Given the above, we think such a discussion about the validity of the claims is relevant for risk managers to decide which method to follow.

* Corresponding author.
E-mail address: bart.koelmans@wur.nl (A.A. Koelmans).

https://doi.org/10.1016/j.trac.2023.117142

Our paper aims to propose essential components for the ecological risk assessment of microplastics and to compare the BR framework with our previously published PDF-based approach, which has been implemented in a risk management framework for the State of California [8,9]. Our criterion for the validity of the risk assessment framework is that it is consistent with the principles of risk assessment science, that it contains an exposure, an effect, and a risk characterization component, and that it has sufficient accuracy and completeness to maintain the complexity of environmentally relevant microplastic mixtures (Table 1). We comment on both frameworks and provide suggestions for a way forward.

2. Quantifying the toxicologically relevant physical properties of microplastics

Microplastic particles found in nature form a continuum of various shapes, sizes, polymer properties, and chemical

Table 1
Components of risk assessment frameworks that aim to maintain the complexity of microplastic particles, and how they are addressed in the PDF [3,5,6,8] and BR frameworks.

Essential component	PDF framework	BR framework
1. Characterisation of physical properties[a]	Lossless probability density functions (PDFs), applicable to all possible characteristics	Simplifying categories, i.e. 6 for size, 3 for shape, 5 for polymer
2. Extent to which the entire microplastic continuum is covered[b]	PDFs cover the entire continuum, e.g. for sizes from 1 to 5000 μm, regardless of analytical limitations.	Covers the particles in a sample, which is thus limited by the analytical method that happens to be used
3. Representativeness of the scale of the assessment[c]	Allows probabilistic system-wide extra- and interpolation while taking system dynamics into account	Limited to the scale of 'snapshot' samples that are assumed to be location-specific
4. Additives[d]	Continuous dose-response relationships, accounts for all chemical exposure pathways, uses PEC/PNEC approach	Simplified to three exposure categories, considering only possible exposure via microplastic, ignoring the other routes of chemical exposure
5. Sorbed chemicals[d]	Continuous dose-response relationships, accounts for all chemical exposure pathways, uses PEC/PNEC approach	Simplified to three exposure categories, considering only possible exposure via microplastic, ignoring the other routes of chemical exposure
6. Chemical exposure scenario[e]	Actual environmental concentrations to approximate the situation in nature	Concentration in the original product
7. Particle bioavailability[f]	Particle size versus organism mouth opening or translocation barrier	Not accounted for
8. Effect assessment[g)]	effect thresholds from standardized tests, combined in e.g. SSD's	Not accounted for
9. Strategy regarding particles to be tested[h]	One environmentally relevant polydisperse mixture of particles, reducing the need for alignments	Sequential testing of many monodisperse particle types, dissimilar to environmental mixtures.
10. Species specificity[i]	Through species specific bioavailability and -sensitivity to particle and chemical effects	Not accounted for
11. Adaptation to habitat type[j]	Habitat specific SSD	Not accounted for
12. Risk characterisation[k]	PEC/PNEC for toxicologically relevant metrics that are motivated from known effect mechanisms	Not accounted for
13. Consistency with known effect mechanisms[l)]	Recognizes the food dilution mechanism, and mechanisms triggered by translocation. Quantitative.	Agnostic, qualitative
14. Coherence with risk assessment in existing policy frameworks[m]	Complies to the ruling risk assessment paradigm.	Not coherent.[n)]
15. Availability of open science tools[o]	Accessible to a wide audience through the ToMEx web application [47].	Not available.
16. Degree of acceptance and integration in science and policy[p]	Implemented in a risk management framework and regulation for California [8,9]. This included an expert elicitation regarding the validity of the concepts and outcomes of the assessment. Used in five scientific studies.	Not yet implemented or used elsewhere

[a] Needed to be able to quantify bioavailability and toxicity caused by characteristics.
[b] Needed to assure no relevant fractions are overlooked. Only if the naturally occurring extremes for all relevant environmental characteristics of microplastics are covered, can the framework be said to maintain the complexity of microplastics.
[c] Needed to ensure that the spatial scale matches that of communities to be protected, and that spatiotemporal scales take into account the variability of exposure concentrations caused by hydrological dynamics in aquatic systems.
[d] Needed to address the contribution to effects caused by additives and sorbed chemicals. Following established concepts in risk assessment science, exposure is expressed as a measured or Predicted Environmental Concentration (eg., PEC), whereas Predicted threshold No-Effect Concentrations are referred to as PNEC. Chemical risk characterisation is quantified by the PEC/PNEC ratio.
[e] The exposure scenario should be environmentally relevant, i.e., reflect the characteristics of exposure as they would occur in nature.
[f] Particles that are not bioaccessible and/or bioavailable should not be taken into account.
[g] The risk depends on the sensitivity of the organism to effects, which must therefore be taken into account. Species Sensitivity Distributions (SSDs) are often used to adequately protect the most sensitive species in the food web.
[h] Impact assessment requires threshold effect concentrations for species, where the concentration refers to the complex mixtures of particles as they occur in the environment. Ideally, the effect concentrations thus relate to environmentally relevant mixtures of particles.
[i] Since the effects of stressors such as microplastic particles depend on species traits, the relevant traits must be taken into account.
[j] It should recognized that species sensitivities can be habitat specific (e.g. freshwater, estuarine water, seawater, sediment, soil), therefore the effect and risk assessment should be as habitat specific as possible.
[k] For risk assessment, a quantitative characterization of the risk (e.g. PEC/PNEC) should be provided.
[l] The assessment needs to be consistent with known effect mechanisms so that the correct exposure and effect metrics can be selected. Only when done correctly can a meaningful and consistent risk characterization be obtained.
[m] Deviating from existing and accepted terminology and concepts known to risk managers is not recommended if it is not actually necessary.
[n] Reports a risk assessment framework of which the outcome, named 'risk of a sample', is a hazard value. Biological relevance remains unclear.
[o] As long as complex algorithms are only described in scientific literature, they can be difficult to access for users such as risk managers. User-friendly tools are therefore recommended.
[p] Acceptance of a scientific theory, model or framework by scientists and managers is an important measure of the validity and value of those products. Older frameworks have an advantage on this criterion.

characteristics [10]. Organisms are not exposed to particles of only one type or category; they are exposed to the full mixture of particles [5,11,12]. Therefore, a true multidimensional framework should do justice to the properties of the continuum with no or as few simplifications as possible. While the BR-framework aims to maintain the complexity of microplastics, it simplifies these continuous characteristics by using a limited number of gross categories. For instance, it proposes only three categories for shape, five for polymer type, and six for size. Within each category, particle diversity is ignored, leaving only a faint reflection of the true multidimensionality of the particles and their interactions in nature (Fig. 1). Because factors such as bioavailability, chemical release kinetics, and particle toxicity are strongly dependent on shape, size, and polymer type, and these dependencies also differ strongly for different species, the use of such coarse categories can lead to a less accurate or incorrect assessment of the actual risk. In addition, the BR-framework only covers the particles found *in a sample*, within the size range targeted by the chosen measurement method. However, these methods have their analytical limitations [13] and do not necessarily represent the size range that aquatic organisms in their environment are exposed to. The BR-framework, therefore, carries this limitation through to the final hazard assessment. Additionally, samples only represent 'snapshots' of the spatiotemporal scales relevant to aquatic communities and are not representative of the actual exposure in the entire catchment area and/or ecosystem under consideration [14].

Methods that avoid these problems have already been described in the PDF-framework literature. The actual continuous nature of microplastics can be described without using simplifying categories through continuous probability density functions (PDFs), which also allow extrapolation of particles found in a sample to the full range from 1 to 5000 μm that organisms encounter in their environment [1,5,6,8,10,14–17]. Calibrated on the properties of thousands of natural particles in habitats relevant to risk assessment, these PDFs describe particle properties with much less loss of information than is possible with the proposed categories in the BR-framework [5]. To date, PDFs have been published for microplastic properties such as size, shape, area, aspect ratio, mass, and polymer density [e.g., [5,10,15,18]]. PDFs for chemical binding affinities [19,20] and equations for release kinetics are also available [21–23]. PDFs can also be constructed for any surface chemistry-related toxicologically relevant polymer-specific feature, according to the concept of affinity spectra [19,20]. To avoid the limited relevance of assessments based on 'snapshot' samples, a method has been developed that probabilistically models exposure based on a system-wide distribution of concentration data covering the ecosystem or habitat scale of the aquatic community to be protected [14].

Bucci and Rochman [7] nevertheless imply that continuous PDFs are a simplification of the dimensions of microplastics relative to their proposed non-continuous categories [7]. While more accurate and complete, continuous PDFs are only simpler in that they require a lower number of mathematical parameters than methods using categories for each of the microplastic dimensions [5,10].

3. Quantifying the toxicologically relevant chemical properties of microplastics

Chemical pollution in our environment is also complex. Aquatic organisms are exposed to a wide variety of chemicals through

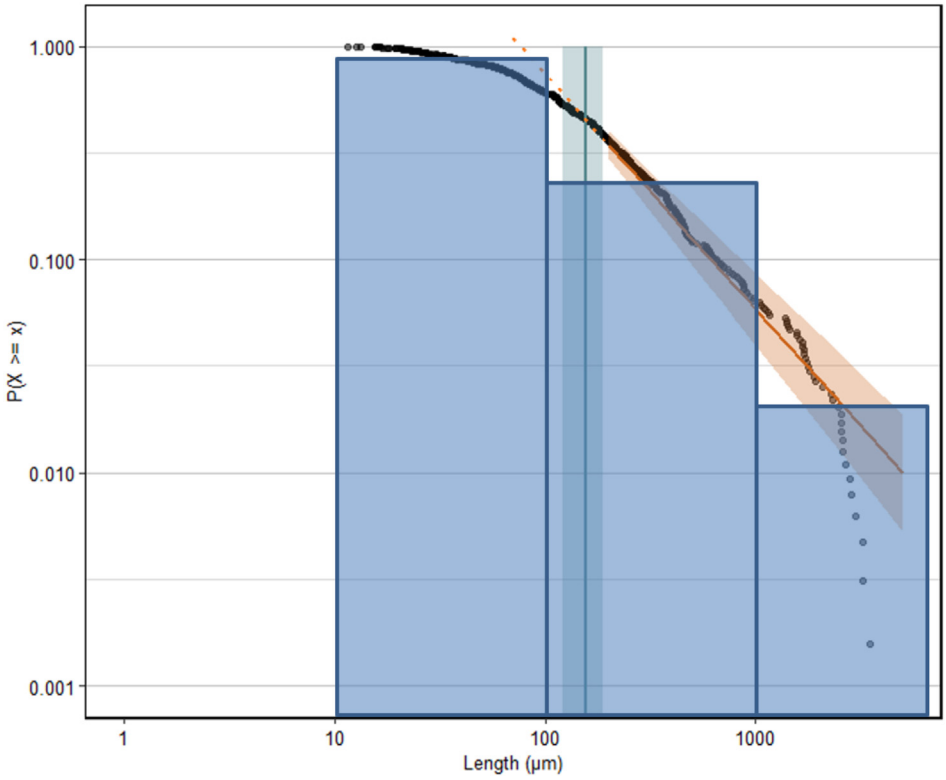

Fig. 1. Illustration of the loss of information by using categories or bins [7], versus lossless capture of microplastic features via probability density functions (PDFs) [5]. The individual data points represent the lengths of the individual particles in an environmentally relevant microplastic mixture (ERMP) (data from Ref. [11]). A mathematical function (PDF) can be fitted to the data to describe it as accurately as possible. The bars represent the size categories proposed in the BR framework for particles between 10 and 5000 μm to represent hazard levels in three gradations. The PDF framework, on the other hand, quantifies the hazard on a continuous scale. The PDF framework also uses the particle length PDF for bioavailability assessment. This is not covered by the BR framework (Table 1).

multiple pathways. Decades of research have given us insight into processes such as bioaccumulation, food web transfer, and biomagnification for all kinds of contaminants [24–27]. The ecologically relevant metric (ERM) for chemicals is concentration, expressed on a continuous scale [1,28]. It is clear that if we want to do justice to the hazards and risks of chemicals, we will have to consider the full realities of exposure to those chemicals, just as we want for the physical characteristics of microplastics. While the BR-framework aims to maintain the complexity of microplastics, in our view it greatly simplifies chemical hazards and chemical exposure. It is proposed to bundle the actual state of chemical exposure into three gross levels of contamination, while it remains unclear how this can be done, confusing the degree of contamination of the particles with that of the water system in which the particles reside, or with proximity to urbanization, industry and agriculture [7]. In addition, only the exposure to chemicals sorbed in the plastics is taken into account, while we know that aquatic organisms are exposed to chemicals through multiple pathways such as through absorption from water or ingestion of food, prey, or other contaminated particles [24–27,29–31]. Consequently, the BR-framework is likely to underestimate the chemical risks that an organism faces, whereas it may overestimate the role of microplastic as a source of exposure. Chemical exposure from microplastics also is highly dependent on chemical fugacity gradients and therefore context-dependent [30–34]. It cannot be inferred solely from the chemical concentration in the plastics. Nevertheless, the BR-framework ignores the state of chemical contamination in the habitat of the organisms and in the organism itself, both in terms of those parallel exposure routes and the need for a gradient for transport. In addition, they ignored the effect-level concentration of the chemicals.

The BR-framework also uses a ranking of the hazard of polymers based on the toxicity of the monomers from which they are made. We find this confusing because potentially toxic monomers are just chemicals and thus already included in the hazard profile of the environmental chemicals. Microplastics are small by definition and the vast majority of secondary microplastics are old [32]. Plastic products and particles fragment and age, allowing additive chemicals and monomers to desorb, while re-adsorbing other monomers and chemicals present in the environment, depending on the fugacity gradients present [34–36]. This means that the state of monomers in original products is not necessarily relevant to the risk in the environment. There are however methods available for chemical exposure and risk assessment that avoid all of these problems, which take into account all exposure routes, including exposure to plastic-associated chemicals [32,34,37,38].

4. Defining and calculating ecological risks for microplastic particles

Even more diverse than microplastic particles and chemicals is life in water. Exposure, effect threshold concentrations, and thus risks of microplastics are different for different species and different life stages of organisms. A multidimensional framework for microplastic risks must therefore also take into account the diversity of species traits. From decades of toxicological and ecotoxicological research, we know that for any given effect mechanism, it is the exposure concentration (or dose) in comparison to the effect thresholds that determine whether an adverse effect is to be expected, and thus whether a risk is to be expected [39,40]. Furthermore, a chemical or particle needs to be bioavailable to be able to cause risk. The BR-framework largely ignores these toxicological principles. Biological information is only used to justify the relative hazard numbers for particle categories, but these remain *relative* numbers and are not per se relevant to effects and risks. For example, a sample with 100 particles per liter, with the lowest BR hazard ranking assigned to all particles, is still toxic to an organism if that organism has a threshold effect concentration lower than 100 particles per liter. Likewise, if all particles are assigned the highest hazard rankings, the sample microplastic concentration could still be well below the threshold effect concentration for the most sensitive species in the ecosystem. In short, the BR-framework says nothing about the actual likeliness of an effect in the environment, and thus says nothing about ecological risks. It lacks an understanding of environmentally relevant exposure and of Paracelsus' principle that “it is the dose that makes the poison.” Nevertheless, Bucci and Rochman [7] refer to the summed hazard values for particles in a sample divided by the sample volume, ignoring actual effect thresholds, as ‘risk of a sample'.

Instead, the PDF-framework uses established methods to quantify the link between exposure and biological effects through dose-response relationships [3,6,8,14,17]. It combines threshold effect concentrations inferred from such relationships, community-level SSD's and PDFs to ensure that toxicologically relevant units and metrics used to quantify exposure and effects are aligned for consistent risk characterization [1,5,6,8,17].

5. The need to develop an alternative framework due to the supposed complexity of microplastic

The past decades have seen major challenges in risk assessment related to complex chemicals and particles, such as heavy metals, organic chemicals, oil, particulate matter, or engineered nanomaterials [41–44]. In doing so, scientists consistently concluded that each of these cases required new tools and concepts, but never that the risk assessment paradigm as such needed to be changed. It is popular among microplastic scientists to say that what they face is unique. However, in no way is the nature of microplastic as a contaminant more complex or unique than any of the aforementioned complex cases. No reasons have so far been presented in the literature why microplastics should not fit into the existing ecological risk assessment paradigm. It is even the other way around; many risk assessment experts have published positively about the use of the existing framework [1,4–6,8,14,15,17,30,31,45–47]. Bucci and Rochman offer no conceptual or mechanistic explanation for their position that the existing framework does not work, other than the claim that “microplastics are unique”. Without an in-depth analysis of existing approaches, they propose to deviate from what has been achieved so far, by proposing a largely *hazard*-based assessment system and framing it as a *risk* assessment framework with a very limited representation of the true multidimensionality of the characteristics of microplastic particles and neglect of effects thresholds. The BR-framework calculates a particle number concentration where for a few categories of particles the number concentration is multiplied by a unitless weighting factor, which takes into account a perceived relative hazard of particle types. Consequently, although not stated in their paper, ‘sample risk’ (see Table 2 in Ref. [7]) has unit particles per liter. However, it remains unclear how environmental managers should use these values, as they are unrelated to actual ecological impacts and therefore to risks. Environmental stewardship is about protecting populations, communities, or iconic species, and it can be confusing for managers to be faced with a framework that provides numbers that are said to define ecological risks when in reality they don't. Existing frameworks provide more intuitive metrics for risks such as PEC/PNEC ratios, the potentially affected fraction of species, or population and community diversity indices through SSDs or ecological modelling [1,4,5,8,17,30]. Such applications already exist for microplastics and we would recommend that environmental managers continue to use such proven concepts.

6. Towards a rational and efficient risk assessment for microplastics

Recognizing that their observed relative toxicity values are preliminary, Bucci and Rochman [7] propose a research program that aims to systematically investigate the relative toxicity of microplastic particles as a function of particle characteristics and to use the results in their framework. The essence of the approach is to always study one particle type and then vary only one of the dimensions while all other dimensions remain constant. We have three comments on their proposal including some alternatives.

First, such laboratory effect data have limited environmental relevance. After all, in the environment, we will never have particle mixtures in which one dimension is constant [5,10]. It cannot be assumed that effects measured in the lab for e.g. monodisperse fragments of 50 μm, for different polymer types, can be translated without corrections to effects of such particles in nature [1,8,48]. After all, in nature, other sizes, shapes, polymers, and chemicals are present at the same time and this influences the effect profile of the 50 μm monodisperse particles. So while such tests can be useful to better understand mechanisms of action, the only ecologically relevant test uses a multidimensional environmentally relevant microplastic (ERMP) mixture, which makes sense in a true multidimensional framework [11,48]. Additionally, the non-alignment between effect data obtained from their proposed laboratory approach and data that would be ecologically relevant can be resolved by using published data alignment methods based on PDFs [1,5,8,15,17,31], but this is not what they propose.

Second, it is both practically and theoretically impossible to change one toxicologically relevant dimension while all others remain constant. For example, if the size changes while shape, polymer, and chemistry remain constant [7], the mass, volume, and surface area of the particles, and the bioavailability of bound chemicals, will change [5]. So that is four toxicologically relevant changes instead of one. We know from toxicology that it is precisely these metrics that are relevant and that they operate via co-acting mechanisms [5,6,8]. Also practically it is impossible because, in the proposed range from 10 nm to 1 mm (Fig. 3 in Ref. [7]), no method is known to synthesize particles of the same shape. So, the actual shape will always differ. This kind of problem exists for all dimensions presented. Another example is changing the polymer type without changing all other relevant dimensions. A different polymer would imply different surface functional groups, but also a different particle density. Because of polymer-specific differences in intra-polymer diffusion coefficients [23], bioavailability and thus chemical toxicity would differ as well. Each of the 'dimensions' therefore actually has several underlying factors, which are often correlated with each other, but these are not addressed in the proposal. The causal relationships are not linear and not univariate. It is therefore more logical that the effect profile of a multidimensional contaminant such as microplastics requires a multivariate interpretation framework.

Third, the reductionist approach is inefficient due to the huge financial and time investment required. The proposed BR-framework distinguishes 6 sizes, 5 shapes, and 5 polymers, and each of these with versus without additives and with versus without 'environmental exposure' [7]. Bucci and Rochman [7] also argue for better quality assurance as suggested by de Ruijter et al. [48]. While we welcome the latter, it implies the use of dose-effect relationships with at least 6 doses, including blanks, positive controls, and $n > 3$ replication [48]. This means that for a single species, their experiment requires $6 \times 5 \times 5 \times 2 \times 2 \times 7 \times 3 = 12{,}600$ exposure test systems. The question of for which species these tests should be done and for which endpoints are not addressed, but risk assessment usually relies on a minimum of 10 species to select data for the most sensitive species in the risk assessment [8,29]. Bucci and Rochman further argue that factors such as biofilm, temperature, and pH must also be taken into account. Suppose we reasonably want to test these factors at four levels each, for each of these 10 species, then the number of test systems becomes more than eight million.

7. Conclusion

We have identified a minimum set of 16 components that we believe are necessary for an ecological risk assessment framework for microplastics, to be consistent with proven elements of risk assessment science and other scientific knowledge (Table 1). Many of these components will also be relevant to human health risk assessments. We critically compared two recent frameworks that aim to capture the risks of microplastic particles in light of these components. Our conclusion is that, when comparing the two risk assessment frameworks in detail, the BR framework seems to lack an effect assessment component that takes into account differences in ecological effect thresholds due to differences in species traits. This means that the BR framework is not a complete risk assessment framework. The characteristics of microplastics are quantified by using a limited number of coarse categories in the BR framework, which does not maintain the complexity of microplastics. The advantage of this approach is that it is simple to communicate and understand. However, the simplifications come at the expense of the accuracy of quantifying bioavailability and dose-effect dependencies for each of the microplastic traits that are relevant to effects. Furthermore, the BR framework underestimates potential risks from microplastic fractions that are not targeted by the analytical methods used.

In contrast, the PDF framework maintains the complexity of microplastic mixtures in a lossless manner using continuous mathematical functions. It uses an effect assessment component, which puts it within the definition of a risk assessment framework. It represents a higher-tier approach because it is more accurate and realistic, but it is conceptually more complex than the BR framework. However, user-friendly tools are available [47]. Key steps to improve risk assessment are (a) improving measurement methods to calibrate PDFs on better datasets, down to the nanoscale if possible, and (b) standardized effect testing with environmentally relevant microplastic (ERMP) mixtures, minimizing the need for alignments [11].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

We thank Merel Kooi and two anonymous reviewers for their valuable contributions to the manuscript. A.A.K. acknowledges funding from the Dutch Research Council Technology Foundation NWO-TTW, project number 13940: Technologies for the Risk Assessment of Microplastics. V.R. and A.A.K. acknowledge funding from CEFIC-LRI, project ECO49: Microplastics Effect Threshold for Aquatic Species (METAS). N.H.B.M.N. is supported by the National Research Foundation of Singapore, Prime Minister's Office under the NRF-NERC-SEAP-2020 grant call, "Understanding the Impact of

Plastic Pollution on Marine Ecosystems in South East Asia (South East Asia Plastics (SEAP)" (Award No. SEAP-2020-0003). B.M.G.B. was funded by the Gieskes Strijbis Fund and the Royal Dutch Academy of Sciences. P.E.R.H. acknowledges the Juan de la Cierva – Formación Research Fellowship (FJC2020–045328-I), financed by MCIN/AEI/10.13039/501100011033, and the European Union "NextGenerationEU/PRTR".

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