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Journal:	*Environmental Science & Technology*
Manuscript ID	es-2018-05297k.R1
Manuscript Type:	Feature
Date Submitted by the Author:	n/a
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Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris

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Keywords: harmonization, legislation, litter, microplastics, plastics, terminology

Synopsis

Plastic pollution is a global issue. However, there is no consensus on how to define and categorize plastic debris, for instance in terms of materials or size classes. As this ambiguity creates miscommunication, we propose a framework to define plastic debris based on material properties and categorize it according to size, shape, color, and origin. This should help to clarify what we actually mean when we talk about plastic debris.

Abstract

The accumulation of plastic litter in natural environments is a global issue. Concerns over potential negative impacts on the economy, wildlife, and human health provide strong incentives for improving the sustainable use of plastics. Despite the many voices raised on the issue, we lack a consensus on how to define and categorize plastic debris. This is evident for microplastics, where inconsistent size classes are used, and where the materials to be included are under debate. While this is inherent in an emerging research field, an ambiguous terminology results in confusion and miscommunication that may compromise progress in research and mitigation measures.

Therefore, we need to be explicit on what exactly we consider plastic debris. Thus, we critically discuss the advantages and disadvantages of a unified terminology, propose a definition and categorization framework and highlight areas of uncertainty.

Going beyond size classes, our framework includes physico-chemical properties (polymer composition, solid state, solubility) as defining criteria and size, shape, color, and origin as classifiers for categorization. Acknowledging the rapid evolution of our knowledge on plastic pollution, our framework will promote consensus-building within the scientific and regulatory community based on a solid scientific foundation.

1 Introduction

Plastic pollution is a substantial environmental problem. Plastic debris, that is, plastic items occurring in natural environments without fulfilling an intended function, is persistent, mobile, and ubiquitous in terrestrial and aquatic environments, including urban, rural, and remote locations. Large plastic litter is readily visible and adversely affects wildlife species through entanglement, ingestion and lacerations.[1] Microscopic plastic debris (i.e., microplastics) has, until recently, largely been an overlooked part of plastic pollution. This has changed in the last decade, over which time growing scientific, public, and political interest has focused on the smaller size fractions, in particular those in the micrometer size range.[2] Today, research into the formation, features, further fragmentation, chemical interactions, environmental fate, and potential impacts of microplastics is increasingly abundant.[3]

The term 'microlitter' was used in 2003 to describe the fine fraction of marine plastic litter with sizes of 63–500 μm.[3] Similarly, mesolitter, macrolitter, and megalitter were defined as having sizes of <5 to 10 mm, <10 to 15 cm or measuring decimeters or more across, respectively.[4] In 2004, the term 'microplastics' was popularized to describe truly microscopic plastic fragments with typical diameters down to ～20 μm.[5] While this paper described the accumulation of microplastics in the seas around the United Kingdom, it did not define them. In 2008, experts attending a meeting hosted by NOAA proposed a working definition in which microplastics are all plastic particles <5 mm in diameter,[6] which has become the most frequently used definition. Although not yet detected in environmental samples, sub-micron sized particles are expected to form in the environment through fragmentation of larger plastics.[7, 8] These have been termed nanoplastics.[9, 10] Due to the evolving research on plastic debris, a certain nomenclature has developed. Nonetheless, the terminology remains ambiguous and conflicting, for instance regarding the size classes (Figure 1). So far, "*[t]here is no internationally agreed definition of the size below which a small piece of plastic should be called a microplastic*".[11]

In the context of this paper, categorization refers to a systematic division of plastic debris into groups according to pre-established criteria. Hereby, plastic objects are grouped based on similarity. A commonly used categorization system is based on size using the prefixes of mega-, macro-, meso-, micro-, and nano. In addition, plastic debris can also be categorized based on their origin, shape, and polymer type.[12] However, a systematic framework for categorizing plastic debris is currently missing.

While most of the discourse on what makes a plastic item, for instance, a “microplastic” focuses on size as only criterion,[13] we first need to revisit the question of what plastics actually are. This is important because – apart from the commodity polymers – there is no consensus on which materials to include in the term ‘plastics’. For instance, some studies consider cellophane, i.e., regenerated cellulose, as plastics[14, 15] while it can be argued that it is not. In addition, definition criteria from polymer sciences are not stringently applicable to plastic debris. For instance, rubber is not plastic according to some polymer chemistry definitions.[16] Yet, environmental researchers consider rubber-containing tire wear a major component of microplastic pollution.[17, 18] The same is true for paint particles. To clarify, we discuss basic physico-chemical properties as ‘definition criteria’ before considering size, shape, color, and origin as ‘classification criteria’ for the categorization of plastic debris.

2 Do we need a common terminology?

The lack of consensus on a definition and categorization of plastic debris results in an ambiguous communication and the generation of incomparable data. While this situation inevitably calls for a harmonization, we need to keep in mind the implications of such a framework. Categorizing plastic debris into different classes (e.g., sizes) implicitly suggests that the items within one category have some 'likeness' whereas plastics in different categories are somehow different. This may be perceived as similarity in hazardous properties or environmental behavior. Such connotation has emerged for the term microplastics, using size as a key feature, already.[19] On the downside, this may point research towards properties that are irrelevant and result in neglecting features that are potentially important. A framework can, thus, shape the research field and affect current and future mitigation measures based on how it frames the problem. This will also affect the risk perception and the hypotheses generated to examine it.[20]

In the area of engineered nanomaterials, the process of agreeing on a common terminology has been ongoing for more than a decade and is under continuous debate[21, 22] and revision.[23] For nanomaterials, the European Commission 'Recommendation on a Definition of Nanomaterials' states that: "*an upper limit of 100 nm is commonly used by general consensus, but there is no scientific evidence to support the appropriateness of this value*."[24] It has been further specified that "*clear [size] boundaries were primarily introduced with the regulatory purpose of the definition in mind rather than for scientific reasons*."[23] Hence, the size boundaries are not scientifically justified but rather based on pragmatic reasons and general consensus. As behavior and toxicity will also depend on properties other than size, a purely scientific definition of nanomaterials may never be achieved – at least not if it shall have any practical value.

For plastic debris, similar considerations do apply: There is no clear scientific justification for the currently applied size boundaries. The 5 mm upper limit for microplastics proposed by NOAA[6] is somewhat biologically informed as particles of this size were considered more likely to be ingested compared to larger items. Still, the decision on size limits is not based on actual evidence but rather on pragmatism.[11]

Ultimately, the question whether to establish a definition/categorization framework for plastic debris is at the heart of two conflicting points of view. On the one hand, there is the notion to refute any attempt to unify the terminology as this restricts scientific freedom and narrows down the scientific focus to what is included in the definition. On the other hand, there is the view that a globally accepted definition is an essential prerequisite to tackle the issue, especially from a regulatory perspective.[25] As environmental scientists, we work in the space between these poles and can neither ignore the importance of academic freedom nor our obligation to support science-based policy-making. While we acknowledge that a flexible, adaptive, and continuously updated framework would be ideal for science, we recognize that this conflicts with regulatory needs and processes. For instance, the control of microplastic emissions will depend on a common definition. Accordingly, the discourse needs to focus on developing a pragmatic and workable framework enabling effective regulation while not restraining scientific freedom.

3 Guiding principles for formulating a definition/categorization framework

When developing a framework for defining and categorizing plastic debris, we considered the following guiding principles, assumptions and disclaimers:

1) A definition/categorization framework should not be tied to current methodological and analytical capabilities as these evolve constantly.
2) A definition/categorization framework should not be limited to size as sole criterion as properties other than size contribute to the impacts of plastic debris.
3) A definition can be based on scientific criteria using the physical and chemical properties of the materials included as plastics.
4) A categorization cannot be purely science-based because the biologically relevant properties needed to categorize plastic objects are not well understood.
5) Accordingly, any categorization will, to some extent, be arbitrary and must be based on conventions formed by consensus and guided by pragmatism.
6) Thus, the proposed definition/categorization framework is a recommendation that aims at promoting consensus-building on a common terminology.
7) Consensus-building in academia is a dynamic process rather than a one-time decision. Thus, the proposed framework must be subjected to criticism and revision.
8) Regardless of the existence of this or any other definition/categorization framework, scientific data should always be reported in the most comprehensive way, that is, in accordance with the latest state of the science.
9) A material should not be excluded from the framework based on its degradability or state of degradation as even “degradable” materials will form smaller fragments before they mineralize.
10) The main audience of this framework are researchers, as a common terminology needs to form in the community producing the primary knowledge on plastic pollution. However, the framework can also serve as point of departure for policy-makers and the regulatory community.

4 Recommendation of a definition/categorization framework for plastic debris

To structure the discussion on what plastic debris is, we propose a framework which differentiates between defining criteria that address basic properties and auxiliary criteria for categorizing plastic debris (principle 3 and 4, Figure 2). According to Merriam-Webster's dictionary, a definition is "*a statement expressing the essential nature of something*." A good question to ask about any definition is therefore: does it actually capture the property that we are trying to define? For plastic debris, we consider the following as relevant defining properties: chemical composition, solid state, and solubility (criteria I-III). These will determine whether a material classifies as 'plastic' and, thus, 'plastic debris' when found in natural environments. For further categorization, we discuss size, shape and structure, color, and origin (criteria IV-VII).

4.1 Criterion I: Chemical composition

The chemical composition is the most fundamental criterion for defining plastic debris. Some disagreement exists on which polymers should be considered 'plastics'. For instance, according to ISO plastic is a "*material which contains as an essential ingredient a high molecular weight polymer and which, at some stage in its processing into finished products, can be shaped by flow.*"[16] In contrast to thermoplastics and thermosets, some elastomers (e.g., rubbers) are excluded from this definition. This mirrors the industrial landscape and, thus, has historic rather than scientific reasons. Questions, therefore, arise whether materials derived from rubber or inorganic/hybrid polymers (e.g., silicone) qualify as plastics. Also, are plastics with a high content of low-molecular weight additives (e.g., polyvinyl chloride (PVC) containing >50% plasticizers) included? And should polymer composites fall under such a definition? Finally, should crystalline fibers, which are not shaped by flow, be excluded from a definition even though they are composed of the same polymers as other plastic debris? These questions reflect the different perspectives of material and environmental sciences.

a. Polymers

As the ISO definition of plastics excludes certain materials, which are relevant in environmental terms (e.g., elastomers), we use a broader definition as point of departure. IUPAC defines a polymer as a "*molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass.*"[26] Typically, polymers have a molecular mass of >10,000 g mol^{-1}.[27]

As a next level, we can use the origin of the polymer as criterion and differentiate between natural and artificial (man-made, synthetic) polymers. With regard to the former, there is agreement that natural polymers (e.g., DNA, proteins, wool, silk, cellulose) are not plastics while synthetic polymers commonly are. Modified natural polymers, natural rubber and cellulose further processed to make the final polymer (rayon and cellophane) for instance, represent a special case. Because these polymers are heavily modified, they can also be considered artificial and should be included in a definition of plastic debris.

The inclusion of natural polymers that have been slightly processed (e.g., dyed wool) is more difficult. This predominantly concerns polymer fibers used for textiles and we do not have sufficient information to benchmark the occurrence and impacts of natural, modified natural, and synthetic fibers, respectively. However, because their essential ingredient is a natural polymer, we propose to exclude slightly modified natural fibers from a definition.[28]

Conventional plastics are petroleum-based and include the commodity plastics polyethylene (PE), polypropylene (PP), polyurethane, polyethylene terephthalate (PET), polystyrene (PS), and PVC. Recently, bio-based plastics synthesized from non-fossil feedstock have entered the market. Bio-based monomers can be used to make the conventional polymers (e.g., bio-PET, bio-PE) or biodegradable polymers such as polylactic acid and polyhydroxyalkanoates.[29] A third type of plastics is mainly produced from inorganic monomers. These inorganic or hybrid polymers – silicone is the most prominent example – are usually excluded from plastics definitions, since they are elastomers. However, because all three polymer classes are synthetic and are emitted to the environment, we recommend including them in a definition of plastic debris.

b. Additives

Plastics can contain a broad range of low molecular weight additives to improve their processability, properties, and performance. They are, thus, an essential part of the formulation. The major classes of additives include plasticizers, stabilizers, flame retardants, flow modifiers, processing aids, impact modifiers, and antioxidants.[30, 31] In addition, pigments, biocides, and fragrances can be added. Additives and other small molecules present in plastics (e.g., monomer residues or by-products formed during production) may be toxicologically relevant when leaching from the material. Nonetheless, they are not of specific importance for a definition because the polymer backbone, not its additive content, defines a plastic material. Polymers containing high amounts of additives (e.g., PVC) represent a special case. According to REACH,[32] substances with an additive content of >50% are not polymers. In contrast, we propose to exclude the additive content as criterion because it will change continuously after the release into in the environment.

c. Copolymers

Some synthetic polymers are produced "*from more than one species of monomer.*"[26] These include copolymers of acrylonitrile-butadiene-styrene (ABS), ethylene-vinyl acetate (EVA), and styrene-butadiene rubber (SBR). ABS and EVA are thermoplastic polymers (i.e., 'plastics' according to ISO) and, thus, can be considered plastic debris when found in the environment. The same argument can be applied to thermoplastic elastomers, such as styrenic block copolymers, thermoplastic olefins, and thermoplastic polyurethanes, which are widely used in automotive manufacturing. In line with the arguments made above, SBR (also an elastomer) and other synthetic rubber copolymers should be included in a definition.

d. Composites

Polymer composites consist of at least two components; the polymer matrix and (non)polymeric reinforcement. Classical thermoset composites include glass fiber-reinforced polyester or graphite reinforced epoxy, both used for instance for boat hulls. This also includes thermoplastics filled with various inorganic materials to reduce costs or improve properties. Likewise, polyester textiles are often mixed with cotton or wool. We recommend including composites into a definition of plastic debris because synthetic polymers are an essential ingredient. However, it remains unknown whether setting a minimum polymer content of a material to qualify as plastics is appropriate and feasible.

Special cases 1: Surface coatings

One special case of composites are paint particles found in the environment. Surface coatings (such as paints) are applied as a thin layer to a surface for aesthetic or protective reasons.[33] Coatings are formulated, multi-component systems consisting of binders, pigments, fillers and extenders, solvents, and additives. Polymers are used as film formers and include (modified) natural resins, curing coating systems (e.g., polyester, alkyds, epoxy resin, urethane resins), and physically drying systems (acryl and vinyl (co)polymers).[33]

The central question for including coating particles in a definition is whether the synthetic polymers used in surface coatings are considered plastics. Recent government reports argue that they should.[34, 35] Indeed, particles originating from dried paints and lacquers containing cured thermosets can be considered plastic debris. Examples are coatings based on polyesters, vinyl esters, polyurethanes as well as epoxy, phenolic, acrylic resins and alkyd.[34] Accordingly, particles derived from paints and surface coatings containing synthetic polymers as an essential ingredient should be included in a definition. However, as in the case of composites, setting a threshold for a minimal polymer content is currently not possible.

Special case 2: Tire wear particles

Driving vehicles releases particles due to the abrasion of tires, termed tire wear particles (TWP). Some agencies have considered TWP to be 'microplastics'[34, 36-38] because tires usually contain 40–60% of synthetic polymers (e.g., SBR or polybutadiene rubber). The exact composition of tires depends on their application.[18] To classify TWP as plastic debris, two questions need to be addressed: First, are rubbers plastics? Here, we argue that they should be covered by the proposed definition (see criterion Ic). Second, do we need to take into account a changing chemical and material composition during weathering? As an example, TWP will aggregate with road particles and form tire wear and road particles (TWRP) with a lower total polymer content. We argue it is not feasible to determine the polymer content of TWRP as this would need to happen for each individual particle. This is also true for other plastic particles forming heteroaggregates with other particulate matter. Accordingly, we propose to refer to the original material and to include TWP/TWRP in the definition because synthetic polymers are an essential ingredient of tires.

4.2 Criterion II: Solid state

While it might be common sense that plastics are solid materials, some polymers can be wax-like, semi-solid or liquid. According to the Global Harmonized System for Classification and Labelling of Chemicals (GHS) a solid substance or mixture "*does not meet the definitions of liquid or gas*." As most polymers have a vapor pressure of <300 kPa (at 50 °C) and an initial melting point of >20 °C (T_m at 101.3 kPa) they are solid.[39] For most materials, the T_m determines the difference between the solid and the liquid state. However, amorphous and semi-crystalline plastics will behave differently when heated. Amorphous polymers (e.g., polymethyl methacrylate, ABS, PS) are hard, brittle materials below their glass transition temperature (T_g), whereas they become viscous and free flowing above. Semi-crystalline polymers (e.g., polyamide, polycarbonate, PE, PET, PP, PVC) have both, a T_g as well as a T_m. These polymers will be hard and brittle below their T_g but ductile, soft, and form stable below their T_m, and liquid above.

Plastics are used both as hard and brittle as well as softer and more ductile materials (plasticized PVC, PE, PP) and depending on molecular weight exist as waxy, semi-solids over a broad temperature range. For some polymers (e.g., rubber, PE, PP, PVC), T_g is relatively low. Accordingly, they are soft solids at ambient temperatures. Nevertheless, semi-crystalline polymers have a T_m high enough to classify them as solid according to GHS and can be included in a definition of plastic debris.

In contrast, amorphous polymers lack a specific T_m. Therefore, we propose to consider the T_g as a defining value. Accordingly, amorphous polymers with a T_g >20 °C should be included in a definition. Here, the properties of the bulk materials should be considered. However, the question remains whether wax-like polymers with a T_g <20 °C should be included as well. In this regard, the combination with other physico-chemical properties, such as viscosity, modulus of elasticity or tension at constant elongation, might be helpful.

Special case 3: Polymer gels

Polymer gels are often perceived as liquid rather than solid, due to their high liquid content and their soft and flexible appearance. However, in macromolecular science a gel is indeed "*a solid composed of at least two components, one of which (polymer) forms a three-dimensional network […] in the medium of the other component (liquid).*"[40] Polymer gels come from a natural (e.g., gelatin, agarose) or synthetic feedstock (polyacrylamide, polyvinyl alcohol (PVA), low molecular weight polyethylene glycol (PEG)) and are used in a wide variety of applications. For instance, polyacrylamide copolymers are used as flocculation agents during wastewater treatment. While these gels are "solid" from a chemical perspective, they will become soft and viscous in water. Although this does not make them benign *per se* (we simply do not know), we argue that polymer gels are not particulate matter once in aquatic environments and should, therefore, be excluded from a definition and treated as an independent category of environmental polymers.

4.3 Criterion III: Solubility

Another important aspect is the polymer's solubility. Most conventional polymers are poorly soluble in water, but some synthetic polymers readily dissolve in water (e.g., PVA or low molecular weight PEG). We propose using solubility as a criterion to define plastic debris and apply the REACH guidance provided by ECHA. Here, a substance is considered poorly soluble if their water solubility is <1 mg L^{-1} at 20 °C.[41] Polymers that are poorly soluble according to REACH should be included in a definition of plastic debris.

4.4 Criterion IV: Size

Size is the criterion most frequently used to categorize plastic debris, with size classes typically attributed with the nomenclature of nano-, micro-, meso-, and macroplastics. Particle size will be of major ecological relevance because it is one important factor determining the item's interaction with biota and its environmental fate.[42-44] Currently, there is no clear consensus on the use of size categories (Figure 1). Often, size limits are operationally defined by the sampling method. As an example, some authors set the lower size limit of microplastics to 333 µm because a 333 µm mesh plankton net is used for sampling.[6]

From a nomenclature point of view, it is intuitive to categorize the plastics based on the conventional units of size. Accordingly, plastics with sizes in the nanometer scale (1–1,000 nm) should be nanoplastics. Following this reasoning and using the SI prefixes for length, microplastics would have sizes of 1–1,000 µm, followed by milliplastics (1–10 mm), centiplastics (1–10 cm), deciplastics (1–10 dm). This, however, conflicts with the current terminology. For example, nanoplastics and microplastics are typically considered to be 1–100 nm and 1–5,000 µm in size, respectively.[45] Accordingly, new size categories, fully consistent with the SI nomenclature, would have little chance of being adopted by the scientific community. As a pragmatic compromise, we propose the following categories:

- Nanoplastics: 1 to <1,000 nm,*
- Microplastics: 1 to <1,000 µm,
- Mesoplastics: 1 to <10 mm,
- Macroplastics: 1 cm and larger.

*To conform to existing definitions of nanomaterials, a sub-division in nanoplastics (1 to <100 nm) and submicron-plastics (100 to <1,000 nm) can be made.

Another important question relates to the dimensions of the plastic item. Is it sufficient that it possesses the given size in one, two or three dimensions to fall into one of the categories?

Current size classes for microplastics refer to the largest dimension of the item. This is straightforward for relatively spherical particles but more ambiguous for irregular particles and fibers.[45] For example, should a fiber with a diameter (i.e., two dimensions) of 500 µm and a length (i.e., one dimension) of 20 mm be classified as microplastic or macroplastic? If two dimensions in the micrometer range would be sufficient to qualify as a microplastic, this would theoretically imply that a thin thread of infinite length would still be a microplastic. This would correspond to the current practice of determining size by filtration through a net of a certain mesh size or by microscopy, whereby two dimensions are considered. However, a classification should not be based on current practices, which may change as the methodology advances. We, therefore, propose to use the largest dimension as classifier for the size category. The rationale behind this is that the largest dimension of an item will mainly determine the ingestion by biota. For fibers, we do recognize that the diameter may be more relevant and suggest that the dimensions used for categorization should then be defined in the specific study.

4.5 Criterion V: Shape and structure

Aside from size, plastic debris is commonly categorized based on shape, structure, and color. Frequent descriptors of shape are: spheres, beads, pellets, foams, fibers, fragments, films, and flakes.[46-49] These are worth revisiting in order to apply a more stringent classification. The first three (spheres, pellets, beads) are often used synonymously. Additionally, the terms ‘beads’ and ‘pellets’ hints towards the origin of the particles, such as microbeads in cosmetics and pre-production pellets used for plastic manufacturing. If the origin of the specific particle can indeed be elucidated this would be an appropriate terminology. However, as this is often challenging it is instead beneficial to adopt more neutral descriptors, such as ‘spheres’ for particles with every point on its surface having the same distance from its center. The terms 'spheroids' and ‘cylindrical pellets’ can be used for approximate spheres and cylindrical shapes, respectively.

‘Fragments’ also represent a rather ambiguous category. It is commonly adopted to describe particles with irregular shape. The term, however, implies that these have been formed by fragmentation in the environment, which is not necessarily the case. For instance, irregular abrasives used in cosmetics are produced as such[50-52] and cannot be distinguished from particles generated by secondary fragmentation. While the category ‘fragment’ is likely to persist in the literature, an alternative and more accurate term is ‘irregular particles’.

The category of ‘films’ is rather straight-forward as this includes planar objects which are considerably smaller in one dimension than in the other two. It is useful to classify films separately and it is often feasible to make that distinction for items >300 µm. Smaller objects tend to overlap and, due to practical constraints, may be pooled with ‘irregular particles’.

Plastics that are significantly longer in one than wide in two dimensions (length-to-diameter ratio) are commonly (and interchangeably) described as fibers or filaments, with both terms describing thread-like structures. Within toxicology there is a long-standing tradition of referring to such structures as fibers rather than filaments.

For some types of fibers, their aspect ratio has been found to determine toxicological responses, for example in the case of asbestos and carbon nanotubes. Hence, from a toxicological perspective it makes sense to distinguish between different shapes of plastic debris using the neutral terminology described above. Additional information on the structure (e.g., material porosity) can be included when relevant and only when it can be established with certainty. For example, the descriptor ‘foams’ can draw unwanted parallels to styrofoam even though several plastic types can be visually similar. A more neutral descriptor for this type of porous materials would be ‘expanded cellular plastics’.

4.6 Criterion VI: Color

Categorizing plastic debris according to color is useful to identify potential sources as well as potential contaminations during sample preparation. As with shape, the color of an object cannot easily be used to deduce the origin. Importantly, color information can be biased as brighter colors are spotted more easily during visual inspection. In contrast, dark, transparent or translucent particles may be underrepresented. In addition, discoloration can take place during weathering as well as sample preparation, which should be considered in data reporting and interpretation. While we do not find color to be crucial in a categorization framework, it can make sense to include color as an additional descriptor. This can be the case in a biological context, where depending on an organism's feeding preferences, some colored plastic objects may be more or less likely to be mistaken as food.[53] As attributing colors may be subjective, the use of a standardized color palette, such as the Pantone Color Matching System, is preferable.

4.7 Optional criterion VII: Origin

The origin of plastic debris is commonly used as a classifier, especially for microplastics, which are categorized in 'primary' and 'secondary' microplastics. In the predominant view, 'primary' refers to microplastics intentionally produced in that size range whereas 'secondary' microplastics are formed in the environment through fragmentation or through wear and tear of plastic-containing items, such as TWP and fibers released from textiles during use.[11] An alternative perspective is that 'primary' also includes microplastics that are inherent by-products of the use of a product ("primary sources"),[35, 37] such as TWP. In that view, secondary microplastics would originate from fragmentation during weathering, only. Since it is challenging, if not impossible, to determine whether a particle has been generated by fragmentation during intentional use or in the environment, we prefer to use the former classification.

From a regulatory point of view, it is relevant to distinguish between primary and secondary origin. This has consequences for risk management[25, 54] as it may enable assigning responsibilities and apply the polluter pays principle. However, from a biological perspective, it does not matter if the plastic object encountered by an organism is intentionally manufactured. In addition, while primary microplastics tend to be more uniform and homogenous (e.g., microbeads), this is not always the case.[50] A subsequent weathering will further change the appearance, rendering a clear-cut distinction between primary and secondary (micro)plastics often infeasible. Because of this ambiguity, we suggest not to use ‘origin’ to categorize plastics unless the primary origin of plastic debris can be established convincingly. One such case is the detection of microbeads originating from ion exchange resins from a specific production site.[55]

5 Moving towards a workable terminology for plastic debris

The research on plastics in the environment is still in its infancy. This makes it an exciting and dynamic field but inevitably entails a certain scientific immaturity with regards to the hypotheses, concepts, and methods applied. This is also true in terms of the terminology we use. To promote consensus-building, we provide a framework for defining and further categorizing ‘plastic debris’. We identify three defining criteria and four classifiers that can be used in such a framework. Based on this, we propose to define ‘plastic debris’ as objects consisting of synthetic or heavily modified natural polymers as an essential ingredient (criterion I) that, when present in natural environments without fulfilling an intended function, are solid (II) and insoluble (III) at 20 °C. We further recommend using the criteria size (IV), shape (V), color (VI), and origin (VII) to further categorize plastic debris (Table 1, Figure 2). Each criterion covers aspects on which consensus is likely as well as elements which are more debatable. Accordingly, the content of the framework cannot be fixed but may be revised as the field evolves. Thus, we welcome critical input by the readers and encourage a broader debate of this matter in the scientific community.

Author contributions. NBH, MW, and TH conceived and wrote the manuscript and produced the figures. All co-authors critically discussed the ideas and concepts presented in, commented on and reviewed the manuscript. All authors commit to organize and support the post-publication consultation.

Acknowledgments. The German Water Chemistry Society supports the expert group “Plastics in the aquatic environment,” whose members (TH, NB, MPH, MH, NI, MW) co-authored the manuscript. MW has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No 660306, from the German Federal Ministry for Transportation and Digital Infrastructure, and the German Federal Ministry for Education and Research (02WRS1378, 01UU1603, 03F0789D).

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Tables

Table 1. Overview of the recommendations for a definition and classification of plastic debris.

Criterion	Recommendation	Examples
Ia: Chemical composition		
✓ Include	All synthetic polymers:	
	▪ Thermoplastics	All commodity plastics
	▪ Thermosets	Polyurethanes, melamine
	▪ Elastomers	Synthetic rubber
	▪ Inorganic/hybrid	Silicone
✓ Include	Heavily modified natural polymers (semi-synthetic)	Vulcanized natural rubber, regenerated cellulose
× Exclude	Slightly modified natural polymers	Dyed natural fibers
Ib: Additives		
✓ Include	All polymers included in Ia disregarding their additive content	Plasticized PVC with >50 % additives
Ic: Copolymers		
✓ Include	All copolymers	ABS, EVA, SBR
Id: Composites		
✓ Include	All composites containing synthetic polymer as essential ingredient	Reinforced polyester and epoxy
✓ Include	All surface coatings containing polymers as essential ingredient	Paints containing polyester, PUR, alkyd, acrylic, epoxy resin
✓ Include	Tire wear (and road) particles	-
? Open question	Is it necessary to define a minimum polymer content?	
II: Solid state		
✓ Include	All polymers with a T_m or T_g >20 °C	See examples in Ia
× Exclude	Polymer gels	PVA, PEG
? Open question	Should wax-like polymers (T_g <20 °C) be included?	
III: Solubility ✓ Include	All polymers with a solubility <1 mg L^{-1} at 20 °C	See examples in Ia
IV: Size	▪ Nanoplastics: 1 to <1,000 nm ▪ Microplastics: 1 to <1,000 µm ▪ Mesoplastics: 1 to <10 mm ▪ Macroplastics: 1 cm and larger The largest dimension of the object determines the category. Comprehensive reporting of dimensions is preferred (e.g., for fibers).	
V: Shape and structure	Spheres: Every surface point has the same distance from the center Spheroid: Imperfect but approximate sphere Cylindrical pellet: Rod-shaped, cylindrical object Fragment: Particle with irregular shape Film: Planar, considerably smaller in one than in the other dimensions Fiber: Significantly longer in one than wide in two dimensions Additional information on the structure (e.g., porosity) can be included.	
VI: Color	Not crucial for a categorization but useful in a biological context (e.g., when color is a cue for ingestion). Use a standardized color palette.	
VII: Origin	Primary: Intentionally produced in a certain size Secondary: Formed by fragmentation in the environment or during use Origin should only be used if the primary origin can be established.	

Figures

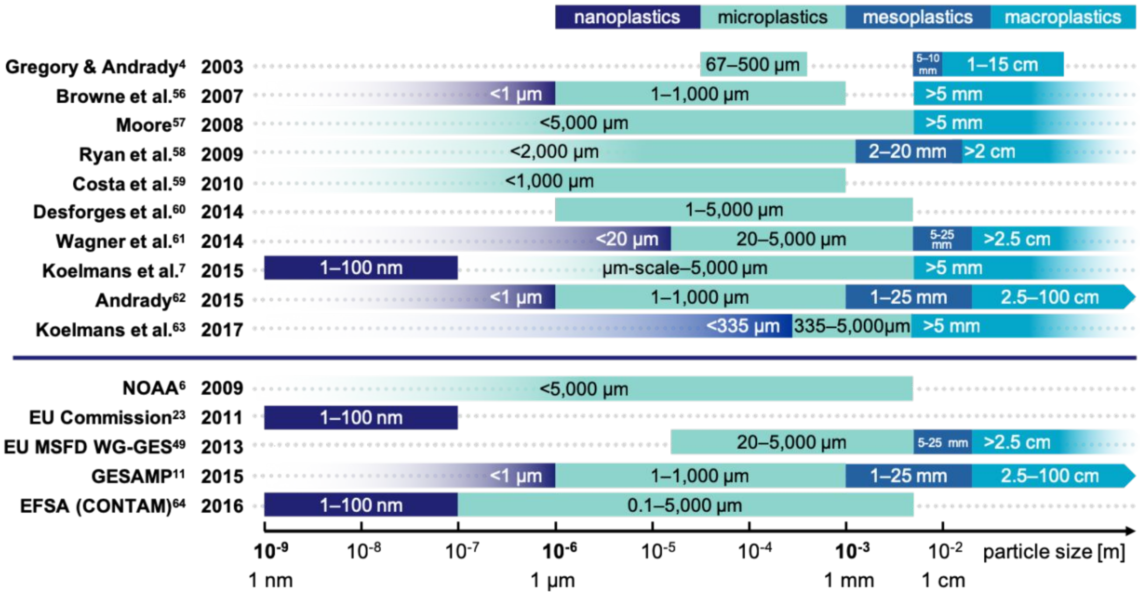


Figure 1. Examples of differences in the categorization of plastic debris according to size as applied (and/or defined) in scientific literature and in institutional reports. It should be noted that this does not represent an exhaustive overview of all used size classes.

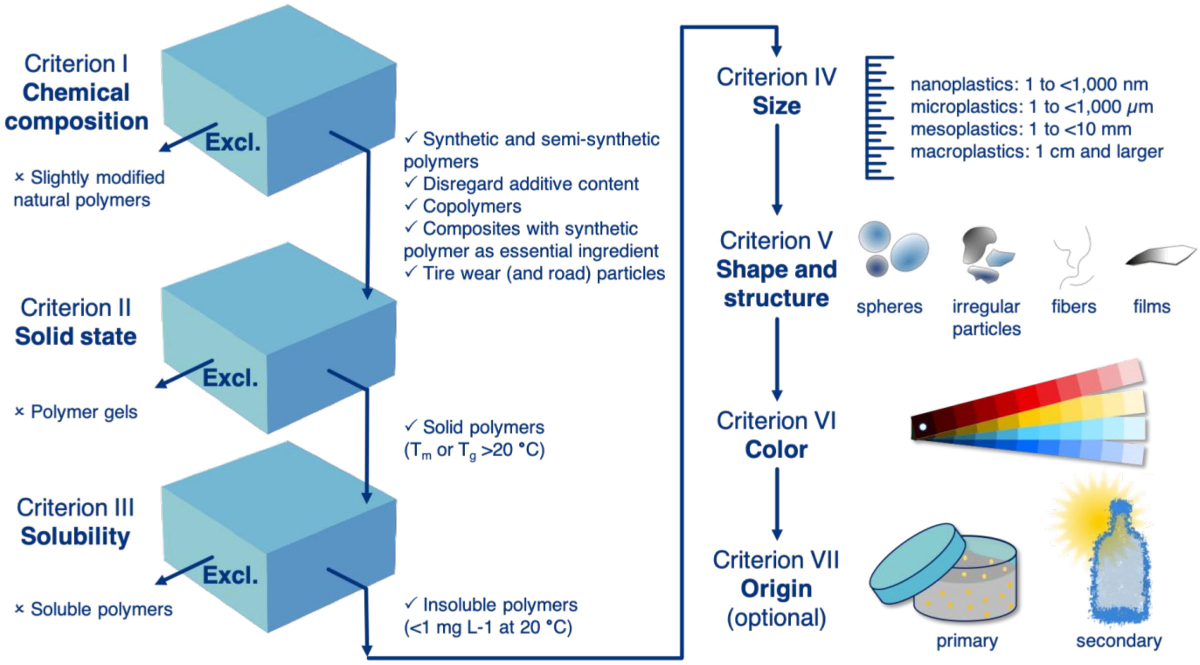
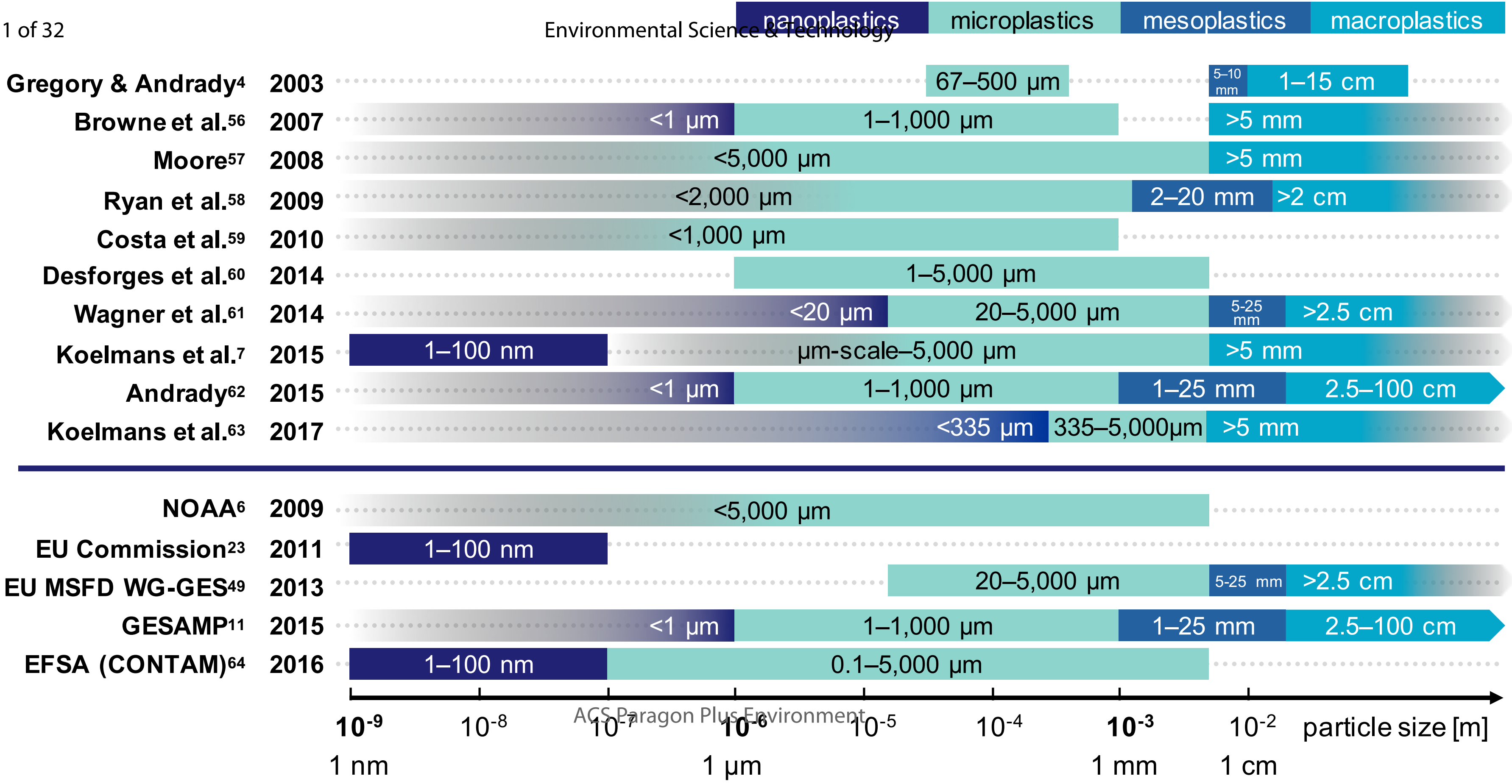
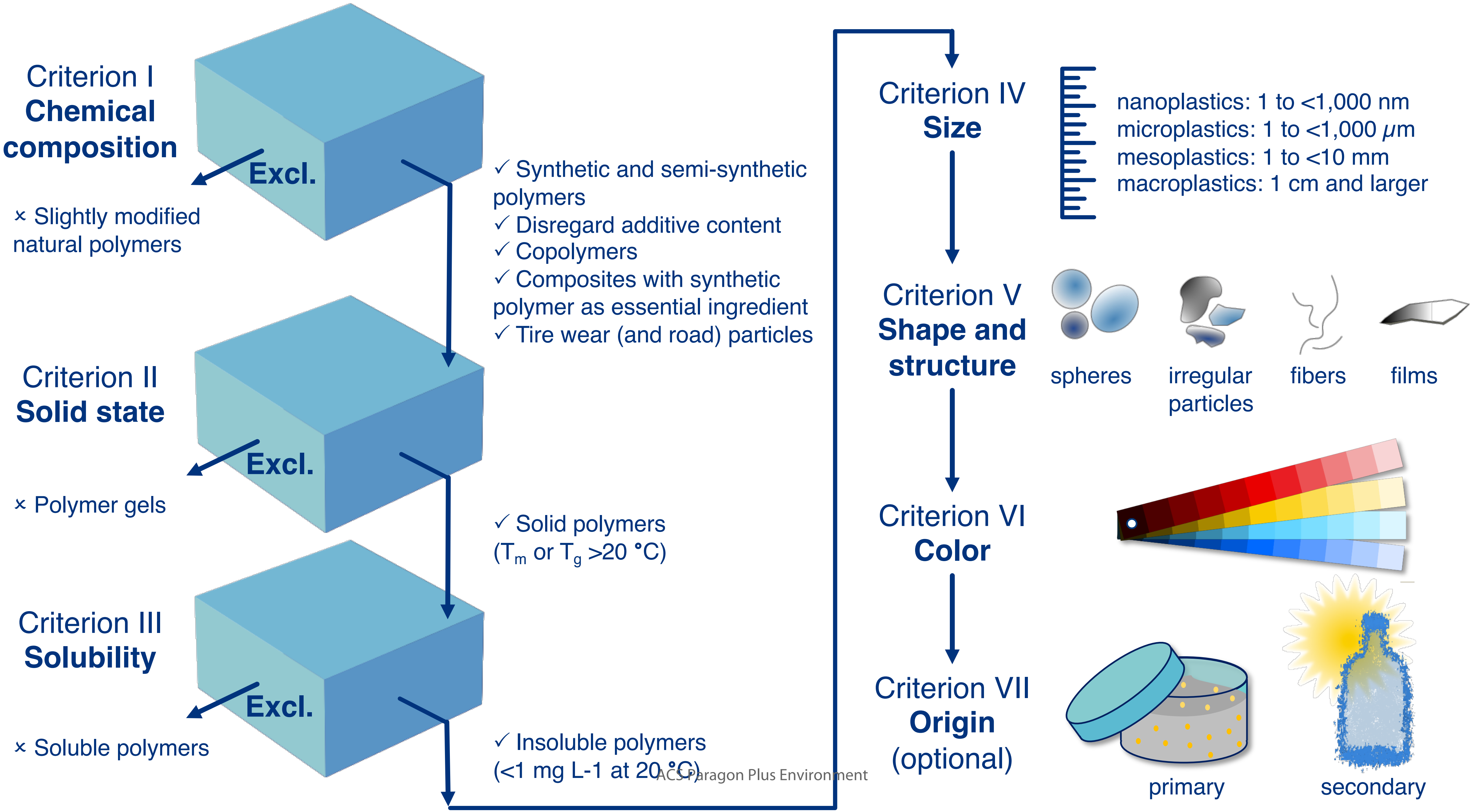


Figure 2. Proposed definition and categorization framework. Excl. = excluded, see Table 1 for details on criteria.


nanoplastics
microplastics
mesoplastics
macroplastics
Gregory & Andrady[4] 2003
67–500 µm
5–10 mm
1–15 cm
Browne et al.[56] 2007
<1 µm
1–1,000 µm
>5 mm
Moore[57] 2008
<5,000 µm
>5 mm
Ryan et al.[58] 2009
<2,000 µm
2–20 mm
>2 cm
Costa et al.[59] 2010
<1,000 µm
Desforges et al.[60] 2014
1–5,000 µm
Wagner et al.[61] 2014
<20 µm
20–5,000 µm
5-25 mm
>2.5 cm
Koelmans et al.[7] 2015
1–100 nm
µm-scale–5,000 µm
>5 mm
Andrady[62] 2015
<1 µm
1–1,000 µm
1–25 mm
2.5–100 cm
Koelmans et al.[63] 2017
<335 µm
335–5,000µm
>5 mm
NOAA[6] 2009
<5,000 µm
EU Commission[23] 2011
1–100 nm
EU MSFD WG-GES[49] 2013
20–5,000 µm
5-25 mm
>2.5 cm
GESAMP[11] 2015
<1 µm
1–1,000 µm
1–25 mm
2.5–100 cm
EFSA (CONTAM)[64] 2016
1–100 nm
0.1–5,000 µm
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
particle size [m]
1 nm
1 µm
1 mm
1 cm



Criterion I
Chemical composition

Excl.

× Slightly modified natural polymers

✓ Synthetic and semi-synthetic polymers
✓ Disregard additive content
✓ Copolymers
✓ Composites with synthetic polymer as essential ingredient
✓ Tire wear (and road) particles

Criterion II
Solid state

Excl.

× Polymer gels

✓ Solid polymers
(T_m or T_g >20 °C)

Criterion III
Solubility

Excl.

× Soluble polymers

✓ Insoluble polymers
(<1 mg L-1 at 20 °C)

Criterion IV
Size

nanoplastics: 1 to <1,000 nm
microplastics: 1 to <1,000 μm
mesoplastics: 1 to <10 mm
macroplastics: 1 cm and larger

Criterion V
Shape and structure

spheres
irregular particles
fibers
films

Criterion VI
Color

Criterion VII
Origin
(optional)

primary
secondary