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Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris

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Complete List of Authors:	Hartmann, Nanna ; Technical University of Denmark, Department of Environmental Engineering Hüffer, Thorsten; Universitat Wien, Department of Environmental Geosciences Thompson, Richard; University of Plymouth, School of Biological and Marine Sciences Hassellöv, Martin; Goteborgs Universitet, Department of Marine Sciences Verschoor, Anja; National Institute for Public Health and the Environment (RIVM) Daugaard, Anders; Technical University of Denmark, Department of Chemical and Biochemical Engineering, Danish Polymer Centre Rist, Sinja; Technical Univeristy of Denmark, DTU Environment Karlsson, Therese; Goteborgs Universitet, Department of Marine Sciences Brennholt, Nicole; Bundesanstalt fur Gewasserkunde, Department Biochemistry and Ecotoxicology Cole, Matt; Plymouth Marine Laboratory Herrling, Maria; Ovivo Switzerland AG Heß, Maren; North Rhine Westphalia State Agency for Nature, Environment and Consumer Protection, Department Water Management, Water Protection Ivleva, Natalia; Technical University Munich, Institute for Hydrochemistry Lusher, Amy; Norwegian Institute for Water Research (NIVA) Wagner, Martin; Norwegian University for Science and Technology, Department of Biology

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1 **Are we speaking the same language? Recommendations for a definition and**
2 **categorization framework for plastic debris**

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4 **Nanna B. Hartmann^{1,*}, Thorsten Hüffer^{2,*}, Richard Thompson³, Martin Hassellöv⁴, Anja**
5 **Verschoor⁵, Anders Egede Daugaard⁶, Sinja Rist¹, Therese Karlsson⁴, Nicole**
6 **Brennholt⁷, Matthew Cole⁸, Maria P. Herrling⁹, Maren Heß¹⁰, Natalia P. Ivleva¹¹, Amy L.**
7 **Lusher¹², Martin Wagner^{13,*}**

8 ¹ Technical University of Denmark, Department of Environmental Engineering,
9 Bygningstorvet B115, 2800 Kgs. Lyngby, Denmark

10 ² University of Vienna, Department of Environmental Geosciences; Environmental Science
11 Research Network; and Research Platform Plastics in the Environment and Society
12 (PLENTY), Althanstrasse 14, 1090 Vienna, Austria

13 ³ School of Biological and Marine Sciences, Plymouth University, Plymouth PL4 8AA, United
14 Kingdom

15 ⁴ University of Gothenburg, Department of Marine Sciences, Kristineberg 566, 45178
16 Fiskebäckskil, Sweden

17 ⁵ National Institute for Public Health and the Environment, Antonie van Leeuwenhoeklaan 9,
18 3721 MA Bilthoven, The Netherlands

19 ⁶ Technical University of Denmark, Department of Chemical and Biochemical Engineering,
20 Danish Polymer Centre, Søtofts Plads B227, 2800 Kgs. Lyngby, Denmark

21 ⁷ Federal Institute of Hydrology, Department Biochemistry and Ecotoxicology, Am Mainzer
22 Tor 1, 56068 Koblenz, Germany

23 ⁸ Marine Ecology & Biodiversity, Plymouth Marine Laboratory, Prospect Place, The Hoe,
24 Plymouth PL1 3DH, United Kingdom

25 ⁹ Ovivo Switzerland AG, Hauptstrasse 192, 4147 Aesch, Switzerland

26 ¹⁰ North Rhine Westphalia State Agency for Nature, Environment and Consumer Protection,
27 Department Water Management, Water Protection, Postfach 101052, 45610
28 Recklinghausen, Germany

29 ¹¹ Technical University of Munich, Institute of Hydrochemistry, Chair of Analytical Chemistry
30 and Water Chemistry, Marchioninstr. 17, 81377 Munich, Germany

31 ¹² Norwegian Institute for Water Research (NIVA), 0349 Oslo, Norway

32 ¹³ Norwegian University of Science and Technology (NTNU), Department of Biology, 7491
33 Trondheim, Norway

34 * Corresponding authors: nibh@env.dtu.dk, thorsten.hueffer@univie.ac.at,
35 martin.wagner@ntnu.no

36

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38

39 **Synopsis**

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

45 Abstract

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

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

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

62 **1 Introduction**

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

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

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

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

105 **2 Do we need a common terminology?**

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

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

129 For plastic debris, similar considerations do apply: There is no clear scientific justification for
130 the currently applied size boundaries. The 5 mm upper limit for microplastics proposed by
131 NOAA⁶ is somewhat biologically informed as particles of this size were considered more

132 likely to be ingested compared to larger items. Still, the decision on size limits is not based
133 on actual evidence but rather on pragmatism.¹¹

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

147 **3 Guiding principles for formulating a definition/categorization framework**

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

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

174 **4 Recommendation of a definition/categorization framework for plastic debris**

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

185

186 **4.1 Criterion I: Chemical composition**

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

200 *a. Polymers*

201 As the ISO definition of plastics excludes certain materials, which are relevant in
202 environmental terms (e.g., elastomers), we use a broader definition as point of departure.
203 IUPAC defines a polymer as a “*molecule of high relative molecular mass, the structure of*
204 *which essentially comprises the multiple repetition of units derived, actually or conceptually,*
205 *from molecules of low relative molecular mass.*”²⁶ Typically, polymers have a molecular mass
206 of >10,000 g mol⁻¹.²⁷

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

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

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

229 *b. Additives*

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

242 *c. Copolymers*

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

251 *d. Composites*

252 Polymer composites consist of at least two components; the polymer matrix and
253 (non)polymeric reinforcement. Classical thermoset composites include glass fiber-reinforced
254 polyester or graphite reinforced epoxy, both used for instance for boat hulls. This also
255 includes thermoplastics filled with various inorganic materials to reduce costs or improve

256 properties. Likewise, polyester textiles are often mixed with cotton or wool. We recommend
257 including composites into a definition of plastic debris because synthetic polymers are an
258 essential ingredient. However, it remains unknown whether setting a minimum polymer
259 content of a material to qualify as plastics is appropriate and feasible.

260 *Special cases 1: Surface coatings*

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

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

275 *Special case 2: Tire wear particles*

276 Driving vehicles releases particles due to the abrasion of tires, termed tire wear particles
277 (TWP). Some agencies have considered TWP to be 'microplastics'^{34, 36-38} because tires
278 usually contain 40–60% of synthetic polymers (e.g., SBR or polybutadiene rubber). The
279 exact composition of tires depends on their application.¹⁸ To classify TWP as plastic debris,
280 two questions need to be addressed: First, are rubbers plastics? Here, we argue that they
281 should be covered by the proposed definition (see criterion Ic). Second, do we need to take
282 into account a changing chemical and material composition during weathering? As an

283 example, TWP will aggregate with road particles and form tire wear and road particles
284 (TWRP) with a lower total polymer content. We argue it is not feasible to determine the
285 polymer content of TWRP as this would need to happen for each individual particle. This is
286 also true for other plastic particles forming heteroaggregates with other particulate matter.
287 Accordingly, we propose to refer to the original material and to include TWP/TWRP in the
288 definition because synthetic polymers are an essential ingredient of tires.

289

290 **4.2 Criterion II: Solid state**

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

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

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

315 *Special case 3: Polymer gels*

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

328

329 **4.3 Criterion III: Solubility**

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

336

337 **4.4 Criterion IV: Size**

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

345 From a nomenclature point of view, it is intuitive to categorize the plastics based on the
346 conventional units of size. Accordingly, plastics with sizes in the nanometer scale (1–1,000
347 nm) should be nanoplastics. Following this reasoning and using the SI prefixes for length,
348 microplastics would have sizes of 1–1,000 μm , followed by milliplastics (1–10 mm),
349 centiplastics (1–10 cm), deciplastics (1–10 dm). This, however, conflicts with the current
350 terminology. For example, nanoplastics and microplastics are typically considered to be 1–
351 100 nm and 1–5,000 μm in size, respectively.⁴⁵ Accordingly, new size categories, fully
352 consistent with the SI nomenclature, would have little chance of being adopted by the
353 scientific community. As a pragmatic compromise, we propose the following categories:

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

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

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

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

376

377 **4.5 Criterion V: Shape and structure**

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

389 'Fragments' also represent a rather ambiguous category. It is commonly adopted to describe
390 particles with irregular shape. The term, however, implies that these have been formed by
391 fragmentation in the environment, which is not necessarily the case. For instance, irregular
392 abrasives used in cosmetics are produced as such⁵⁰⁻⁵² and cannot be distinguished from
393 particles generated by secondary fragmentation. While the category 'fragment' is likely to
394 persist in the literature, an alternative and more accurate term is 'irregular particles'.

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

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

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

411

412 **4.6 Criterion VI: Color**

413 Categorizing plastic debris according to color is useful to identify potential sources as well as
414 potential contaminations during sample preparation. As with shape, the color of an object
415 cannot easily be used to deduce the origin. Importantly, color information can be biased as

416 brighter colors are spotted more easily during visual inspection. In contrast, dark, transparent
417 or translucent particles may be underrepresented. In addition, discoloration can take place
418 during weathering as well as sample preparation, which should be considered in data
419 reporting and interpretation. While we do not find color to be crucial in a categorization
420 framework, it can make sense to include color as an additional descriptor. This can be the
421 case in a biological context, where depending on an organism's feeding preferences, some
422 colored plastic objects may be more or less likely to be mistaken as food.⁵³ As attributing
423 colors may be subjective, the use of a standardized color palette, such as the Pantone Color
424 Matching System, is preferable.

425

426 **4.7 Optional criterion VII: Origin**

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

438 From a regulatory point of view, it is relevant to distinguish between primary and secondary
439 origin. This has consequences for risk management^{25, 54} as it may enable assigning
440 responsibilities and apply the polluter pays principle. However, from a biological perspective,
441 it does not matter if the plastic object encountered by an organism is intentionally
442 manufactured. In addition, while primary microplastics tend to be more uniform and

443 homogenous (e.g., microbeads), this is not always the case.⁵⁰ A subsequent weathering will
444 further change the appearance, rendering a clear-cut distinction between primary and
445 secondary (micro)plastics often infeasible. Because of this ambiguity, we suggest not to use
446 'origin' to categorize plastics unless the primary origin of plastic debris can be established
447 convincingly. One such case is the detection of microbeads originating from ion exchange
448 resins from a specific production site.⁵⁵

449 **5 Moving towards a workable terminology for plastic debris**

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

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642 **Tables**

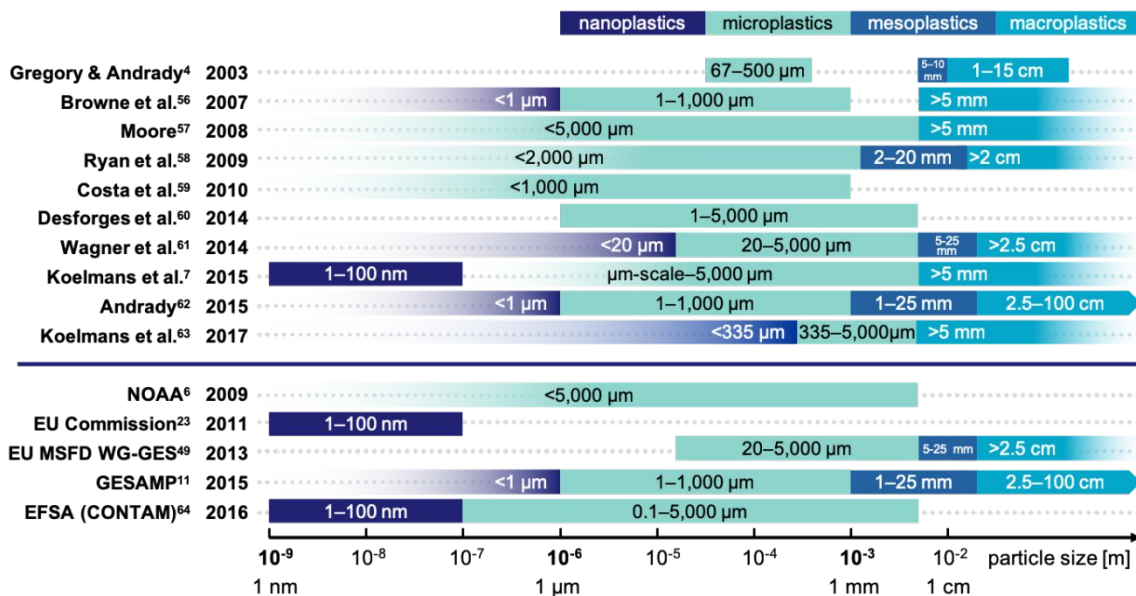
643 Table 1. Overview of the recommendations for a definition and classification of plastic debris.

Criterion	Recommendation	Examples
Ia: Chemical composition		
✓ Include	All synthetic polymers: <ul style="list-style-type: none"> ▪ Thermoplastics ▪ Thermosets ▪ Elastomers ▪ Inorganic/hybrid 	All commodity plastics Polyurethanes, melamine Synthetic rubber 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		
	<ul style="list-style-type: none"> ▪ 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.	

644

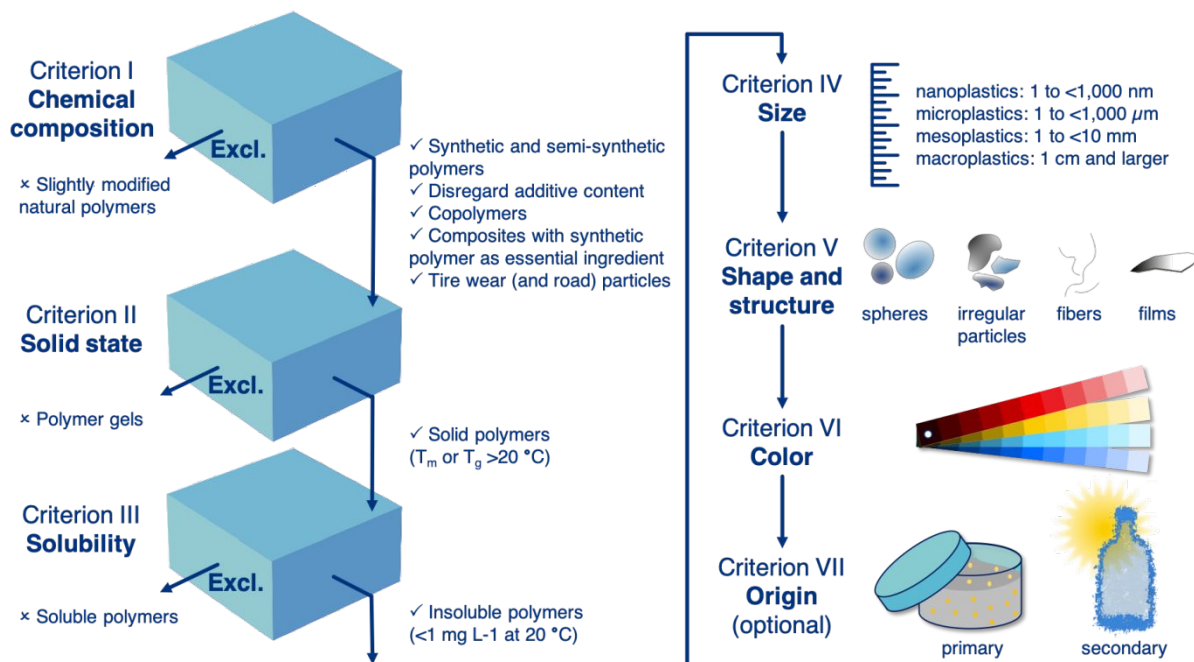
645 **Figures**

646



647

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



651

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

