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1 **Foraminifera and plastic pollution: knowledge gaps and research opportunities**

2

3 Vincent M.P. Bouchet<sup>1,\*</sup>, Laurent Seuront<sup>1,2,3</sup>, Akira Tsujimoto<sup>4</sup>, Julien Richirt,<sup>1,8</sup> Fabrizio  
4 Frontalini<sup>5</sup>, Masashi Tsuchiya<sup>6</sup>, Misako Matsuba<sup>7</sup>, Hidetaka Nomaki<sup>8</sup>

5 <sup>1</sup> Univ. Lille, CNRS, Univ. Littoral Côte d'Opale, IRD, UMR8187, LOG, Laboratoire  
6 d'Océanologie et de Géosciences, Station Marine de Wimereux, F 59000 Lille, France

7 <sup>2</sup> Department of Marine Energy and Resource, Tokyo University of Marine Science and  
8 Technology, 4-5-7 Konan, Minato-ku, Tokyo, 108-8477, Japan

9 <sup>3</sup> Department of Zoology and Entomology, Rhodes University, Grahamstown, 6140, South  
10 Africa

11 <sup>4</sup> Faculty of Education, Shimane University, 1060 Nishikawatsu-cho, Matsue-  
12 shi, Shimane, 690-8504, Japan

13 <sup>5</sup> Department of Pure and Applied Sciences, Università degli Studi di Urbino “Carlo Bo”,  
14 61029, Urbino, Italy

15 <sup>6</sup> Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and  
16 Technology (JAMSTEC), 2-15 Natsushima-cho, Yokosuka 237-0061, Japan

17 <sup>7</sup> Biodiversity Division, National Institute of Environmental Studies, 16-2 Onogawa, Tsukuba,  
18 Ibaraki, 305-8506, Japan

19 <sup>8</sup> X-star, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15  
20 Natsushima-cho, Yokosuka 237-0061, Japan

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22 KEYWORDS. emerging pollutants, coastal habitats, biology, ecology, ecosystem functioning

23

24 ABSTRACT

25 Plastic has become one of the most ubiquitous and environmentally threatening sources of  
26 pollution in the Anthropocene. Beyond the conspicuous visual impact and physical damages,  
27 plastics both carry and release a cocktail of harmful chemicals, such as monomers, additives  
28 and persistent organic pollutants. Here we show through a review of the scientific literature  
29 dealing with both plastic pollution and benthic foraminifera (Rhizaria), that despite their  
30 critical roles in the structure and function of benthic ecosystems, only 0.4% of studies have  
31 investigated the effects of micro- and nano-plastics on this group. Consequently, we urge to  
32 consider benthic foraminifera in plastic pollution studies *via* a tentative roadmap that includes  
33 (i) the use of their biological, physiological and behavioral responses that may unveil the  
34 effects of microplastics and nanoplastics and (ii) the evaluation of the indicative value of  
35 foraminiferal species to serve as proxies for the degree of pollution. This appears particularly  
36 timely in the context of the development of management strategies to restore coastal  
37 ecosystems.

38

39 **Introduction**

40 Plastic pollution in marine environments has been reported as early as 1970 (Carpenter and  
41 Smith Jr 1972) with an increasing interest until the mid-1980s (Bean 1987). It nevertheless  
42 took nearly two additional decades to fully acknowledge the extent of the related  
43 environmental issues (Thompson et al. 2004). Due to both the exponential increase in plastic  
44 production (i.e., from 1.5 Mt in 1950 to 368 Mt in 2019, PlasticsEurope 2020) and the  
45 mismanagement of plastic waste (one third of the plastic waste (32 million Mt) from 93% of  
46 the world's population was classified as mismanaged in 2010, Borrelle et al. 2020), the 5 to 13

47 Mt of plastics discharged into the ocean every year, are expected to reach to up to 90 Mt/year  
48 by 2030 under business-as-usual scenarios (Borrelle et al. 2020). As an inherently durable  
49 material, plastic debris persist in the environment and are dispersed over long distances by  
50 winds and water currents (Alimi et al. 2018). The potential threats related to plastic debris *via*  
51 ingestion or leaching of contaminants (additives and persistent organic pollutants, see review  
52 in Delaeter et al. 2022) have been identified as a major global conservation issue and a key  
53 priority for research (Vegter et al. 2014, Harrison and Hester 2019, Seuront et al. 2022).

54 Plastic debris typically constantly degrade and fragment into smaller and smaller pieces  
55 over time under UV radiation and wave actions to eventually form microplastics (<5 mm;  
56 MPs) and nanoplastics (<100 nm; NPs). These small particles continuously sink towards the  
57 seafloor where they are typically buried in unvegetated and vegetated sediments in subtidal  
58 and intertidal coastal areas (Cozzolino et al. 2020). Noticeably, coastal ecosystems like  
59 seagrass and macroalgal meadows (Cozzolino et al. 2020), mussel beds (Nicastro et al. 2022),  
60 coral reefs (Reichert et al. 2022), tidal marshes and mangroves act as barriers against the  
61 dispersal of MPs and NPs debris towards the marine environment (Martin et al. 2020). As  
62 such, coastal habitats are major sinks for MPs and NPs, which enter long-term sequestration  
63 in sediments (Martin et al. 2020). As a consequence, plastic pollution may interfere with the  
64 key role played by living organisms in coastal ecosystems in mitigating the effects of climate  
65 change by storing carbon dioxide (CO<sub>2</sub>) in sediments (Taillardat et al. 2018). Yet, the effects  
66 of plastic burial on the benthic biocoenosis of intertidal areas and coastal shallow-waters have  
67 been largely overlooked.

68 Of the studies that have explicitly tested the effects of plastic on benthic species, relatively  
69 few have attempted to consider MPs and NPs pollution and meiofaunal species which, for the  
70 most part, are invisible to the naked eye, but are nevertheless crucial elements of coastal  
71 benthic ecosystems (Schratzberger and Ingels 2018). In particular, meiobenthic foraminifera

72 are an important component of these coastal ecosystems. Amongst meiobenthic organisms  
73 (<1 mm), benthic foraminifera (Rhizaria) may represent up to 50% of the benthic eukaryotic  
74 biomass in coastal sediments (Moodley et al. 2000). They also contribute significantly to the  
75 carbon and nitrogen biogeochemical cycles in coastal ecosystems (Jauffrais et al. 2019,  
76 Choquel et al. 2021). They occupy a major trophic position through bacterivory, herbivory or  
77 carnivory (Nomaki et al. 2008, Chronopoulou et al. 2019). They also actively participate in  
78 the benthic ecosystem functioning *via* sediment mixing and bioirrigation, hence enhancing the  
79 fluxes of particulate and dissolved elements at the sediment-water interface (Bouchet and  
80 Seuront 2020, Deldicq et al. 2020, Deldicq et al. 2021a). In addition, foraminifera can  
81 accumulate large quantities of nitrate in their cell and reduce it through denitrification under  
82 low-oxygen conditions (Risgaard-Petersen et al. 2006, Piña-Ochoa et al. 2010, Choquel et al.  
83 2021); their contribution to the nitrogen cycle being, for instance, up to 70% in the North Sea  
84 (Piña-Ochoa et al. 2010) or ranging from 50% to 100% in Swedish fjords (Choquel et al.  
85 2021). In the context of biomonitoring, benthic foraminifera have been shown to be good  
86 sentinel of the health of benthic habitats (Armynot du Châtelet et al. 2004). Due to their  
87 sensitivity to environmental changes, shifts in species composition of benthic foraminiferal  
88 communities quickly reflect changes in environmental conditions (Schönfeld et al. 2012).  
89 Hence, they are used as indicators of pollution (e.g. Alve 1995, Francescangeli et al. 2016,  
90 Polovodova Asteman et al. 2015), such as oil spills (e.g. Morvan et al. 2004), drill cutting  
91 (e.g. Mojtahid et al. 2006), element trace metals (e.g. Armynot du Châtelet et al. 2004), urban  
92 sewage (e.g. Melis et al. 2019), and aquaculture (e.g. He et al. 2019). They are also considered  
93 as accurate bioassay in ecotoxicological experiments which reported test (shell)  
94 malformations (Le Cadre and Debenay 2006), alteration of the growth (Denoyelle et al.  
95 2012), oxydative stress (Frontalini et al. 2018a), physiological changes (Losada Ros et al.  
96 2020), proteom modifications (Ciacci et al. 2022) and changes in species composition of

97 foraminiferal communities in mesocosm (Frontalini et al. 2018b) in response to, respectively,  
98 copper, oil-based drilling muds, element trace metals, cadmium and mercury exposure.

99 Because of the recognized fundamental role of foraminifera in the coastal benthic realm  
100 (Moodley et al. 1998, LeKieffre et al. 2018), it is an important concern how MPs and NPs can  
101 affect them. Specifically, plastic burial in benthic sediments may lead to the ingestion of MPs  
102 or NPs and to long-term exposure of benthic foraminifera to a variety of additives and  
103 chemicals leaching from plastic items in the sediment. Element trace metals, for instance,  
104 which may accumulate onto and then leach from weathered plastic surface, are known to be  
105 harmful for foraminifera (e.g. Le Cadre and Debenay 2006, Frontalini et al. 2018a, 2018b).  
106 Noticeably, a wide range of physiological and ultrastructural impairments (e.g., involving  
107 thickening of organic lining of test, mitochondrial degeneration, proliferation of degradation  
108 vacuoles, lysosomes, residual bodies and the increased production of neutral lipids and of  
109 reactive oxygen species) have been reported in benthic foraminifera exposed to element trace  
110 metals (Frontalini et al. 2018a), as well as morphological abnormalities and decreased growth  
111 rate (Le Cadre and Debenay 2006, Denoyelle et al. 2012). In addition, sediment anoxia  
112 induced by plastic accumulation in the marine litter (Krause et al. 2020) may also contribute  
113 to shape benthic foraminifera communities and promote low-oxygen-tolerant species. On the  
114 basis of the above evidences, it seems legitimate to hypothesize that benthic foraminifera  
115 would be highly affected by plastic pollution.

116 In this context, through a systematic review, this study quantifies the current state of  
117 plastic pollution research on benthic foraminifera, presents key results, and summarizes  
118 perspectives that warrant further study. Here, we highlight why foraminifera should be given  
119 more emphasis in studies aiming to understand the effect of plastics on the benthic  
120 biocoenosis of intertidal areas and coastal shallow-waters. We further suggest a way forward  
121 toward consolidating research and policy efforts to better address the effect of plastic

122 pollution as a potential driver of benthic foraminiferal community structure and role in the  
123 functioning of such key habitats.

124

## 125 **Methods**

126

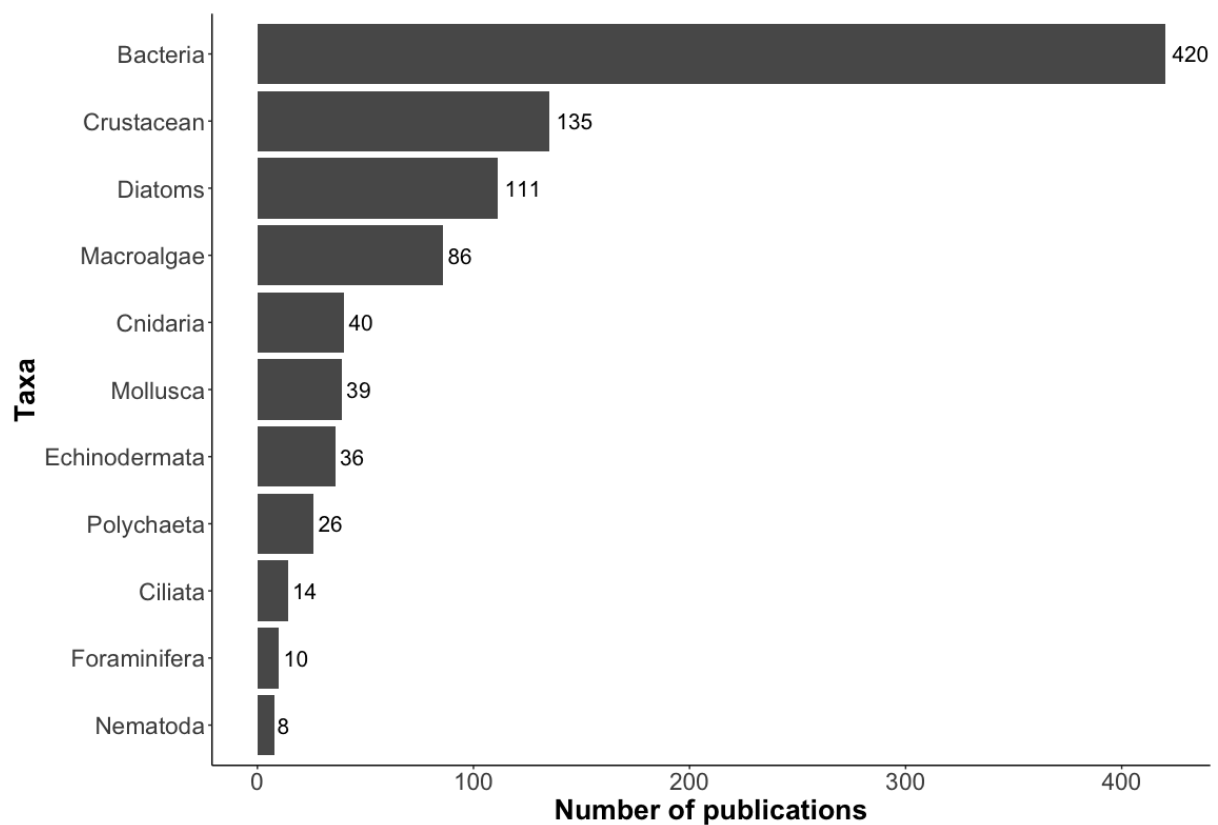
127 The field of research dedicated to plastic pollution in benthic marine ecosystems is  
128 currently one of the most prolific. A literature search was performed in the Web of Science  
129 (last accessed on January, 13, 2023) using the words plastic (i.e. 'plastic\*'), marine (i.e.  
130 'marine') and benthic (i.e. 'benth\*'). A total of 928 publications were returned. To evaluate  
131 the research effort for the main taxa encountered in benthic coastal habitats, the literature  
132 search was refined through the use of different combinations of keywords (i.e. 'bacteria\*',  
133 'crustacean\*', 'diatoms\*', 'macroalgae\*', 'cnidaria\*', 'mollusca\*', 'echinodermata\*',  
134 'polychaeta', 'ciliata\*', 'nematoda\*', 'foraminifera', respectively, together with 'plastic\*',  
135 'marine' and/or 'intertidal' and/or 'coastal', and 'benth\*'). The reference lists within these  
136 studies were also scrutinized to identify additional relevant studies. For this opinion paper, we  
137 only included English-written studies that assessed the impact of plastic pollution on the  
138 above-mentioned taxa. A total of 925 studies were selected. This literature search allowed us  
139 to evaluate the status of the research on benthic foraminifera and plastic pollution compared  
140 to other biological components of benthic ecosystems.

141

### 142 **Plastic pollution and benthic foraminifera: the big void**

143 Among the studies that considered the effect of plastic pollution on marine organisms, a  
144 vast majority (i.e., 81%) essentially targeted bacteria, algae and crustaceans (Fig. 1). Protists  
145 were critically underrepresented (i.e., 2%) and amongst the 24 papers that considered them,  
146 ten of these studies focused on benthic foraminifera; amongst which four observed benthic

147 foraminifera on floating and benthic plastic debris (Jorissen 2014, Finger 2017, Birarda et al.  
148 2021, Subías-Baratau et al. 2022), four focused on the inclusion of plastic particles in  
149 foraminiferal tests (Tsuchiya and Nomaki 2019, Birarda et al. 2021, Joppien et al. 2022a,  
150 Romano et al. 2023) and only four *stricto sensu* monitored the effect of MPs or NPs (Ciacci et  
151 al. 2019, Langlet et al. 2020, Birarda et al. 2021, Joppien et al. 2022b). A recent review  
152 (Delaeter et al. 2022) showed that, in plastic leachates-related studies, only 0.64% studies  
153 considered benthic foraminifera, while about 98% were on macro-invertebrates. Note that,  
154 according to our literature survey, there is still no study considering the impact of plastic  
155 pollution on planktic foraminifera. In short, regardless of coastal ecosystems, the assessment  
156 of MPs and NPs impacts on foraminifera overwhelmingly lags behind other marine species.  
157



158

159 **Figure 1.** Research effort (number of publications) considering the physical and toxic effects  
160 of plastic pollution for the most relevant marine benthic taxa.



161

162 Drifting and benthic plastic debris may be colonized by benthic foraminifera (Jorissen  
163 2014, Finger 2017, Birarda et al. 2021, Subías-Baratau et al. 2022). This may contribute to the  
164 dispersion of benthic foraminifera, and their introduction outside their natural range as  
165 observed on rafted plastic items with shallow-water foraminiferal fouling transported by  
166 currents from Japan to Hawaii and North-America (Finger 2017).

167 Foraminifera have mainly four types of tests: those that assemble calcium carbonate crystals  
168 constructed intracellularly and build tests (porcelaneous test), those that crystallized calcium  
169 carbonate (mainly) extracellularly (hyaline), those that collect sediment particle in the habitat  
170 for a test (agglutinated), and those with an organic membrane. Plastic particles were found to  
171 be included in the test of hyaline (Joppien et al. 2022a) and agglutinated foraminifera  
172 (Tsuchiya and Nomaki 2019, Birarda et al. 2021, Romano et al. 2023), and, as such, might  
173 further be transferred to predators of foraminifera like gastropods, copepods, polychaetes,  
174 decapods, polychaetes and fishes (Buzas and Carle 1979, Culver and Lipps 2003, Nomaki et  
175 al. 2008). Inclusion of plastic particles into the test of benthic foraminifera may likely expose  
176 them to the harmful effects of plastic additives; see Delaeter et al. (2022) for a specific review  
177 on the impacts of plastic leachates on organisms.

178 Amongst the only four papers dealing with the *stricto sensu* influence of plastic on benthic  
179 foraminifera (see details in Table 1), three dealt with the effect of particles (Ciacci et al. 2019,  
180 Birarda et al. 2021, Joppien et al. 2022b) and two with the effects of additives (Langlet et al.  
181 2020, Birarda et al. 2021). Noticeably, the exposition and ingestion of NPs of polystyrene (1  
182 mg.L<sup>-1</sup>) induced physiological stress by promoting the accumulation of neutral lipids and  
183 enhanced reactive oxygen species production in *Ammonia parkinsoniana* (Ciacci et al. 2019).  
184 In the presence of seawater-soaked polyethylene MPs (1 particle.mL<sup>-1</sup>), the coral-reef species  
185 *Amphistegina gibbosa* indifferently fed on MPs and on *Artemia* sp. nauplii (Joppien et al.

186 2022b). The heterotrophic behavior of this symbiont-bearing species was clearly altered;  
187 hence, it had to be more reliant on autotrophy. Furthermore, *Rosalina bradyi*, *Textularia*  
188 *bocki*, and *Lobatula lobatula* were found to colonize *in situ* a plastic bag (most likely  
189 polyethylene) buried in the sediment (Birarda et al. 2021). The accumulation of protein beta-  
190 sheets was observed in all three species, a typical feature observed during oxidative stress  
191 cytotoxicity (Novak et al. 2019). The authors hypothesized that the accumulation of MPs  
192 debris and additives both in the cytoplasm and agglutinated test (i.e., *T. bocki*) may alter the  
193 biomineralization process in foraminifera. Laboratory experiments further showed that the  
194 plastic additive bis-(2-ethylhexyl) phthalate ( $0.3 \text{ mg.L}^{-1}$ ) can be incorporated in the cytoplasm  
195 of *R. globularis* (Birarda et al. 2021). However, the intertidal foraminifera *Haynesina*  
196 *germanica* did not show any change in motion behavior nor in respiration rate when exposed  
197 to leachates from virgin polypropylene pellets (20 and 200 mg of pellets.L<sup>-1</sup>; Langlet et al.  
198 2020).

199 These limited number of studies have partially explored the potential hazard of plastic  
200 contamination of foraminifera in suggesting that MPs and NPs may interfere in the feeding  
201 behavior of benthic foraminifera and generate physiological stress. However, they do not  
202 allow to draw any robust conclusion, in particular because of the heterogeneity between  
203 studies in terms of targeted foraminiferal species, type of plastic polymer, sizes and  
204 concentrations of plastic particles, exposure time and measured parameters (Table 1), which  
205 altogether further hampers any comparison among these works. Hence, we emphasize that our  
206 knowledge is entirely insufficient for an integrated understanding of MPs and NPs effects on  
207 foraminifera, as evidenced by the fact that the response is apparently dependent on the type of  
208 plastic and foraminiferal species.

209 Given the ubiquity and extent of plastic pollution, the ever-growing number of studies  
210 assessing the effect of plastics on a wide range of organisms and the aforementioned potential

211 ecological role of benthic foraminifera in key coastal habitats, it is striking that they have  
212 been disregarded for so long, which further stresses the need to amend the *status quo*. The  
213 lack of attention to a group as dominant in coastal sediments as foraminifera has received  
214 from the scientific community is no longer justified neither on methodological nor ecological  
215 grounds.

Table 1: Publications on the effects of plastic on benthic foraminifera: studied species, plastic types and methodological approaches.

Study	Species	Symbiont/ Chloroplast	Habitat	Type of study	Polymer/Additives	Particles size	Exposure	Concentration	Time of the exposure	Parameters
Birarda et al. 2021	<i>Rosalina globularis</i>	None	Temperate, Coastal, shallow-water	Experimental	Phtalate (DEHP)	/	Additive	0.3 mg.L <sup>-1</sup>	7 weeks	Oxydative stress
	<i>Rosalina bradyi</i> , <i>Textularia bocki</i> , <i>Cibicides lobatulus</i>	None	Temperate, Coastal, shallow-water	<i>In situ</i>	Polyethylene	Plastic bag	Particles and additive	/	/	Particle inclusion in the test, Oxydative stress
Ciacchi et al. 2019	<i>Ammonia parkinsoniana</i>	None	Temperate, Coastal, shallow-water	Experimental	Polystyrene	42 nm	Particles	1 mg.L <sup>-1</sup>	24h	Ultrastructural and physiological changes (oxydative stress)
Joppien et al. 2022b	<i>Amphistegina gibbosa</i>	Symbiont-bearing	Tropical, Coral reefs, shallow-water	Experimental	Polyethylene terephthalate	150-300 $\mu$ m	Particles	1 and 2 particles.mL <sup>-1</sup>	24h	Feeding behavior ( <i>Artemia</i> sp. versus plastic particles)
Langlet et al. 2020	<i>Haynesina germanica</i>	Kleptoplastic	Temperate, Coastal, Intertidal	Experimental	Polypropylene	3.3-4.7 mm	Leachates (24h in seawater)	20 and 200 mL of pellets.L <sup>-1</sup>	10h	Motion behavior, Respiration

217

218 **Benthic foraminifera: culprits and victims of plastic pollution?**

219 It is generally recognized that MPs and NPs have a negative impact on organisms (e.g.  
220 Delaeter et al. 2022), but this is not confirmed to be true for foraminifera. Ironically, benthic  
221 foraminifera may not be only prime suspects but also guilty of sequestering both MPs and  
222 NPs in sediment through their bioturbation activity that would actively transfer plastic  
223 particles from the water-sediment interface to the sediment matrix. Noticeably, they are able  
224 to burrow particles in the size range (10-125  $\mu\text{m}$ ) of MPs (Gross 2002). This may help to  
225 isolate plastic particles from biologically active area (surface sediments) to less active area,  
226 and promote fossilization of MPs and NPs. However, sub-sediments may also constitute a  
227 reservoir where plastics are trapped and be further re-introduced in the food-web by benthic  
228 organisms feeding in this compartment (Sandgaard et al. 2023). In addition, the inclusion of  
229 plastic particles in the test of hyaline and agglutinated benthic foraminifera (Tsuchiya and  
230 Nomaki 2019, Birarda et al. 2021, Joppien et al. 2022a, Romano et al. 2023) possibly  
231 contributes to the transfer of plastic particles and additives through the food web, and to the  
232 trapping of MPs and NPs in the sediment. In this specific context, benthic foraminifera  
233 became their own victims as the burial of MPs and NPs is likely to expose them to ever  
234 increasing concentrations of the countless additives and chemicals carried by plastic items.  
235 We do not yet have evidence of whether they are culprits or victims, but at the very least,  
236 benthic foraminifera that take up plastic provide an archive for the accumulation of MPs and  
237 NPs in marine habitats, and this is *in fine* likely to provide additional evidence of how plastic  
238 can be considered as a key stratigraphic indicator of the Anthropocene as a distinctive strata  
239 component (Corcoran et al. 2015, Zalasiewicz et al. 2016, Dibley 2018). We hence advocate  
240 for more comprehensive research programs (*i*) to understand the role of benthic foraminifera

241 in plastic trapping in sediments, and (ii) to improve our poor knowledge of the effect of  
242 plastic particles and their leachates on benthic foraminifera.

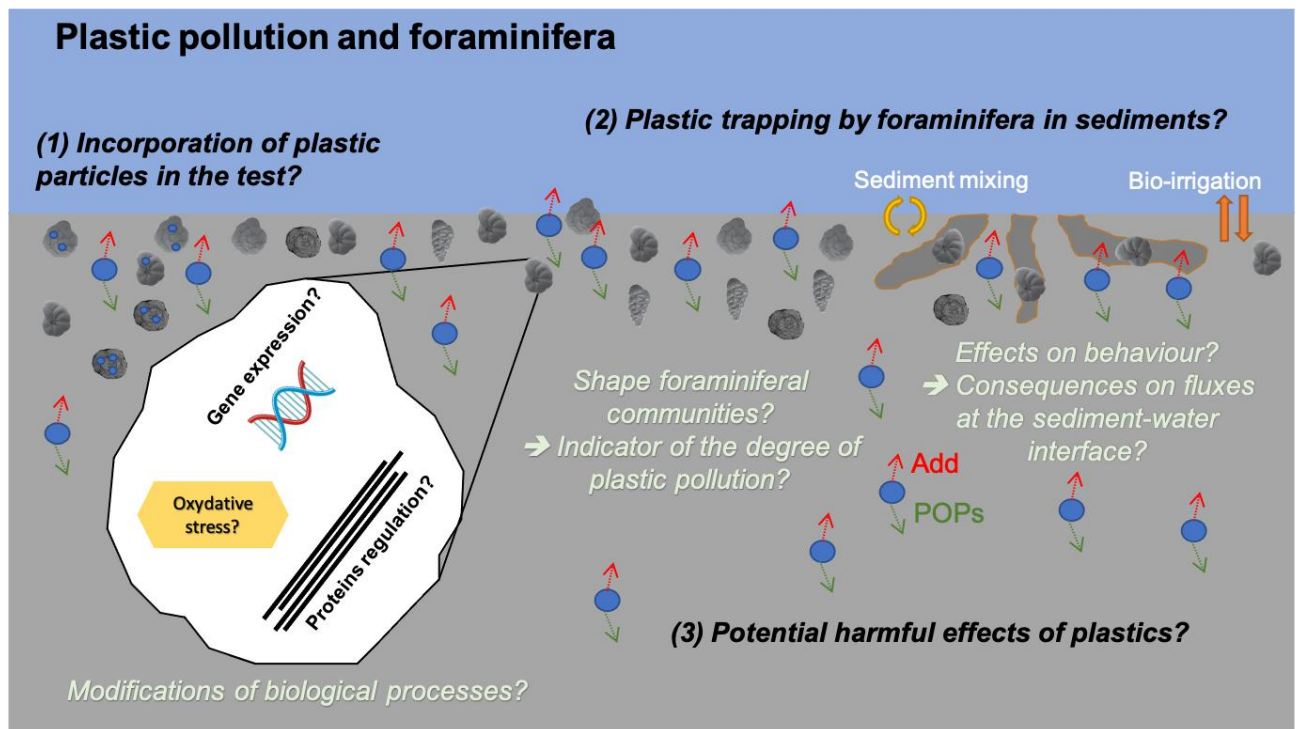
243 The assessment of the pernicious non-lethal effects of MPs and NPs on organisms is a  
244 challenge in the benthic coastal realm, particularly in minute organisms like benthic  
245 foraminifera that represent an emerging model in coastal ecosystems. Despite their noticeable  
246 small number relative to the available literature (see Fig. 1), the recent studies on the response  
247 of benthic foraminifera to various aspects of plastic exposure (Ciacci et al. 2019, Langlet et al.  
248 2020, Birarda et al. 2021, Joppien et al. 2022b) have stressed how critical it is to understand  
249 why, how and under which environmental conditions MPs and NPs affect benthic  
250 foraminifera, and we plea to address the following scientific questions (Fig. 2):

251 (1) What are the processes involved in the integration of plastic particles in foraminiferal test?  
252 In particular, is this particle size- and/or concentration-dependent? Does this occur during  
253 shell construction that includes calcification and agglutination or *via* ingestion? Does this  
254 enhance the exposure of benthic foraminifera to plastic?

255 (2) Does sediment reworking by benthic foraminifera contribute to MPs and NPs  
256 accumulation in coastal sediments?

257 (3) What are the potential harmful effects of plastic on benthic foraminifera at community  
258 level, individual level, and cellular level?

259 (4) *In fine*, do the harmful effects of MPs and NPs alter the role of foraminifera in the benthic  
260 ecosystem functioning?



261

262 Figure 2. Schematic of the questions to be tackled to understand (1) how much plastic  
 263 particles are incorporated in foraminiferal test, (2) to what extent foraminifera may contribute  
 264 to the trapping of MPs and NPs in coastal sediments and (3) the potential harmful effect of  
 265 plastic on (a) species composition of foraminiferal communities (community level), (b)  
 266 behavior (individual level), (c) cellular alterations and physiological changes (cellular level),  
 267 and (4) the possible consequences on the benthic ecosystem functioning *i.e.* sediment mixing  
 268 and bioirrigation. These questions are intended to shed light on the emerging opportunities of  
 269 benthic foraminifera as proxies for the characterization of plastic pollution in coastal  
 270 ecosystems. (Filled blue circles: MPs/NPs particles, Add: additives, POPs: persistent organic  
 271 pollutants)

272

273 Addressing those questions can be achieved in future researches that should—and ideally  
 274 concurrently—monitor the hazards of MPs and NPs exposure at different levels from cells to  
 275 communities in the following roadmap:

276 (i) Cellular level: Underlying mechanisms behind the responses observed at the individual  
277 level can be understood through the study of cellular alterations and physiological changes.  
278 For instance, recent advances in omics technologies have provided new tools to understand  
279 the effects of contaminants, which, in turn, may serve as biomarkers to be used in  
280 environmental monitoring as early warning of pollution (Tomanek 2011; Ciacci et al. 2022).  
281 In details, the response of benthic foraminifera to MPs and NPs particles and leachates are  
282 now deeply accessible through the advance in transcriptomics (Titelboim et al. 2020),  
283 proteomics (Stuhr et al. 2018) and microscopy (Frontalini et al. 2019). In addition, alterations  
284 in the proteome can, for instance, have consequences on the fitness (i.e. reproductive success)  
285 of an organism.

286 (ii) Individual level: While pernicious non-lethal effects of MPs and NPs may likely not be  
287 easy to observe in communities, targeted experiments on foraminiferal individuals with  
288 environmentally relevant concentrations and focusing on specific biological features known to  
289 respond to contamination can address such limitations. Specifically, motion behavior is an  
290 acknowledged keystone process behind the success of foraging, mate-finding and habitat  
291 selection (Bowler and Benton 2005). Motion behavior is still, however, the forgotten child of  
292 foraminiferal ecology, despite its increasingly recognized variability (Seuront and Bouchet  
293 2015, Jauffrais et al. 2016) and role in bioturbation (Bouchet and Seuront 2020, Deldicq et al.  
294 2020, Deldicq et al. 2021a). In addition, benthic foraminiferal behavior is affected in the  
295 presence of a stressor (gravity, organic matter, temperature; Seuront and Bouchet 2015,  
296 Jauffrais et al. 2016, Deldicq et al. 2021b) that may have further consequences on their search  
297 for food and for the optimal microhabitat. In this context, investigating the behavioral changes  
298 induced by MPs and NPs on benthic foraminifera will contribute to improve our  
299 understanding of the effects of plastic pollution on their survival, may serve to predict  
300 population-level effects.



301 We further stress that measurements suggested at points *i)* and *ii)* does not require long-term  
302 incubation and recent studies confirmed they can be easily performed on foraminifera, which  
303 may facilitate their implementation.

304 *(iii)* Community level: MPs and NPs may implicitly alter the quality of habitats inhabited by  
305 benthic foraminifera, hence undermine the survival of some species, and ultimately constrain  
306 the composition of foraminiferal communities. To reveal the response of community  
307 composition to MPs and NPs, it is essential to monitor their spatial distribution through joint  
308 *in situ* sampling surveys of MPs, NPs, and foraminiferal species. By applying spatial models,  
309 *i.e.*, spatial varying coefficient model (Murakami et al. 2017, Matsuba et al. 2020), to these  
310 spatial data, it may be possible to predict the distribution and composition of foraminiferal  
311 communities in response to spatial patterns of MPs and NPs and their concentrations in  
312 sediments, as well as ocean environmental factors (e.g. current velocity) that affect the  
313 distribution of MPs and NPs. Such a modeling approach would be one way to determine how  
314 MPs and NPs pollution, coupled with macro-environmental changes in the ocean, including  
315 climate change, could affect foraminiferal communities. In addition, taking advantage of the  
316 recent development of the use of benthic foraminifera to assess ecological quality statuses  
317 (Alve et al. 2016, Bouchet et al. 2021, Parent et al. 2021), it may provide an opportunity to  
318 develop an index of the degree of plastic pollution in coastal ecosystems sediment through the  
319 identification of indicator species of the presence/absence of MPs and NPs. Finally, a better  
320 understanding of benthic foraminiferal community response to plastic pollution will  
321 eventually help to grasp their role in marine ecosystems functioning.

322

### 323 **Conclusion**

324 Benthic foraminifera offer a putatively endless sets of opportunities to tackle the question of  
325 the potential harmful effects of plastic pollution, from the cellular to the community level. We  
326 plea here to embrace the opportunity to see in these abundant but minute—though highly

327 neglected (see Fig. 1)—organisms a unique prospect to refine our understanding of the effects  
328 of one of the main environmental threats of the “Anthropocene” on the structure and functions  
329 at play behind the future of coastal ecosystems under climate change. *In fine*, foraminifera  
330 will provide proxies of the history and the degree of plastic pollution on the benthic  
331 ecosystem. Last but not the least, there is, to date, no study on the interaction between plastic  
332 and planktic foraminifera, although they may be in contact with MPs and NPs in the water  
333 column. This last aspect must also deserve more attention in the future.

334

## 335 AUTHOR INFORMATION

### 336 **Corresponding Author**

337 \* Vincent M.P. Bouchet, [vincent.bouchet@univ-lille.fr](mailto:vincent.bouchet@univ-lille.fr)

### 338 **Author Contributions**

339 L.S., H.N. and V.M.P.B conceived the idea of the paper. L.S. and V.M.P.B. wrote the original  
340 draft. The manuscript was written through contributions of all authors. All authors have given  
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### 349 **Competing interests statement**

350 The authors have no competing interests to declare.

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