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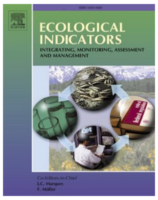

Review

Monitoring microplastic pollution: The potential and limitations of *Nephrops norvegicus*

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ABSTRACT

Microplastics are a major global concern in the marine environment. The use of marine biota to monitor MP pollution has been previously highlighted as a method of providing data. This review focuses on the current data available on the presence of microplastics in *Nephrops norvegicus*, a commercially important seafood species, highlighting the advantages and limitations of the species to determine its potential use for monitoring microplastic pollution. At present, there is no harmonized and standardised methodologies for microplastic analysis available, therefore, this review has proposed future research on microplastics at a European scale. Given the complexity of microplastics present in the marine environment, the authors recommend a more holistic approach with the integration of *Nephrops* and sediments along with other species and matrices to cover all ecosystem compartments to provide a comprehensive database of microplastic levels and trends in the marine environment.

1. Introduction

A large component of marine litter, defined as "…persistent, manufactured or processed solid material that is discarded, disposed of, or abandoned in the marine and coastal environment", is plastic (Galgani et al. 2010, IUCN 2021). Global plastic production has been increasing exponentially in recent years (Ritchie and Roser 2018), with approximately 390 million tonnes produced in 2021 (Plastics Europe 2022). With time, plastic litter in the marine environment fragments into smaller pieces of plastics known as microplastics (MPs) due to environmental weathering and degradation (Thompson et al. 2004) or they can originate from cosmetics and synthetic fabrics manufactured to size (Cole et al. 2011, Auta et al. 2017). MPs are defined as "any synthetic solid particles of different shapes, with sizes ranging from 1 µm to 5 mm of items that are of primary or secondary manufacturing origin, which are insoluble in water" (Arthur et al. 2009, Frias and Nash 2019). The first report of MPs in the marine environment dates back to the early 1970's (Carpenter and Smith 1972), however, little scientific acknowledgement was given to the discovery at the time (Andrady 2011). It took approximately 30 to 40 years for this topic to become a contaminant of emerging concern and be widely reported in the environment and scientific journals (Ryan 2015). MPs in the marine environment originate from a variety of sources, both from land-based and marine and/or maritime-based sources, and pathways (e.g., rivers, etc.) (Ng and Obbard 2006, Siegfried et al. 2017, Deshpande et al. 2020, Rehm et al. 2021) and have been recorded in all marine matrices explored to date as well as pervading water, land, and air (Schwarz et al. 2019, Zhang et al. 2020, Rehm et al. 2021). Furthermore, these contaminants of emerging concern have the potential to persist in the environment for hundreds of years thus leading to a continuous exposure for marine biota (Barnes et al. 2009, Li et al. 2016b).

Owing to their small size, MPs have been reportedly ingested by a range of marine organisms from crustaceans to cetaceans (Wójcik-Fudalewska et al. 2016, Zhu et al. 2019, Joyce et al. 2022a). MPs in biota are of particular interest due to potential ecological risks associated with leaching substances and long-term exposure (Au et al. 2015, Yin et al. 2022). The ingestion of MPs by marine organisms has been shown to cause various adverse effects in experimental exposures, from reduction of fertility and reproduction rates to physiological and biochemical responses (Foley et al. 2018). The ubiquitous nature of MPs has led to an

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increased interest in commercially important seafood species due to the potential for these contaminants to enter the human food chain, affect seafood security and have negative consequences for fishery sustainability in the future (Smith et al. 2018, De-la-Torre 2020, Cunningham et al. 2022). This has raised the interest of several governmental agencies, non-governmental organisations, and academic institutions worldwide in monitoring ecosystem health (Burger 2006, EC 2008); thus, the need for proposal of model organisms or indicator species for monitoring purposes increased consequently (Fossi et al. 2018, Cau et al. 2019, Macali and Bergami 2020). Such organisms are often used to assess the quality of the environment as well as forecast changes resulting from anthropogenic pressures (Holt and Miller 2011).

Many species are used worldwide to monitor changes in their surrounding environment, as it is the case of phyto- and zooplankton, which are commonly used for water quality analysis on a global scale (Devlin et al. 2012, Jiang et al. 2014, Pourafrasyabi and Ramezanpour 2014). Bivalve molluscs are extensively used, with mussels of the genus *Mytilus spp*. being the most common in monitoring programmes (e.g., Mussel Watch Programme). This programme, started by NOAA in the United States of America, is the longest-running contaminant monitoring program in U.S waters, monitoring inorganic and organic contaminants (Viñas et al. 2012). In Europe, the Mussel Watch Programme is implemented in the Mediterranean and Black Seas (Thébault et al. 2008). Furthermore, the OSPAR Coordinated Environment Monitoring Programme (CEMP) uses mussels as a bioindicator to monitor and measure the concentrations of toxic metallic elements such as mercury (Hg), cadmium (Cd), lead (Pb); polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs) and other pollutants (OSPAR 2022c). Other fish and shellfish species are also used under OSPAR CEMP guidelines, for example Dab (*Limanda Limanda*) is used for the monitoring of PCBs in biota (OSPAR 2022e).

Within the European Union (EU), efforts in monitoring plastic contamination are put in place by the Marine Strategy Framework Directive (MSFD) (Galgani et al. 2010, Wenneker and Oosterbaan 2010, van Franeker et al. 2021, Barry et al. 2023). To reduce marine litter, and plastic consequently, EU adopted a strategy in the Circular Economy action plan in 2018, which aimed to reduce plastic waste in the environment including the reduction of MPs in products and their unintentional release into the environment (Crippa et al. 2019). Most of the assessments to date have focused on the monitoring of macro-plastics in the marine environment and the development of indicators for plastic pollution (Wenneker and Oosterbaan 2010, OSPAR 2015). The monitoring of beach litter and seafloor litter is currently being carried out in the OSPAR Maritime Area under descriptor 10 of the MSFD which aims to protect the marine environment in relation to marine litter "*Properties and quantities of marine litter do not cause harm to the coastal and marine environment*" (EC 2008). An example of a species used to monitor plastic levels and trends is the Northern Fulmar (*Fulmarus glacialis*), which is used to quantify the spatial and temporal patterns and trends of floating plastic abundances in the North Sea (Van Franeker et al. 2011). The monitoring of plastics retrieved from the stomach of beached seabirds is carried out under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) system of Ecological Quality Objectives (EcoQOs) which has been included in the MSFD (van Franeker et al. 2021). In addition, in the EU the stomach contents of the loggerhead turtle (*Caretta caretta)* have been proposed to assess plastic pollution and use the levels recorded as a guideline to reach the MFSD's Good Environmental Status (GES) (Domènech et al. 2019). The development of a new OSPAR indicator for the monitoring of MPs in the marine environment is currently underway using seafloor sediments (OSPAR 2022b).

It is noted that no single species can cover all environmental matrices, and a holistic monitoring approach incorporating other matrices such as sediment and benthic organisms may be the ideal management tool. Nevertheless, an indicator species can play an important role in contributing to a monitoring programme (Lusher et al. 2017, Bonanno and Orlando-Bonaca 2018, Pagter et al. 2020a). While there have been various taxa including fish, crustaceans, and molluscs s proposed as potential monitoring tools/indicator species, none have yet been assigned for MP pollution at a European level (Beyer et al. 2017, Garcia-Garin et al. 2019, Xu et al. 2020, Kılıç and Yücel 2022). Mussels are the most widely recommended (Beyer et al. 2017, Li et al. 2019) owing to their status as an established bioindicator, their global distribution, ease of sampling, feeding strategy, high tolerance to a wide variety of environmental parameters and potential link to MPs entering the human food chain (Van Cauwenberghe and Janssen 2014, Li et al. 2016a, Li et al. 2019). Although mussels have been recorded to ingest fibres of up to 4.7 mm (Li et al. 2016a), they are much more efficient in retaining smaller particles (ca. 1–25 μm) (Wang et al. 2021). Therefore, the retention may not be reflective of MP pollution in an area when the size range of MP is considered (Frias and Nash 2019). In addition, despite their effectiveness as bioindicators, both jellyfish and mussels are largely found to coastal areas (Houghton et al. 2006, Beyer et al. 2017, Li et al. 2019) and their MP loads reflect MPs in the water column, which may not represent the bioavailable MPs in other environmental compartments. Over time, it has been demonstrated that the largest and heaviest fraction of MPs would sink to the seafloor (Woodall et al. 2014), where it accumulates over years. Hence the coupled use of multiple indicator species would provide a more complete or holistic assessment of MP pollution.

Direct MP pollution measurements in the marine environment, especially in deeper waters, are often technically challenging and costly, with no monitoring guidelines in place. However, information is required for environmental management and assessment of the bioavailable MPs. Currently there is no bioindicator or scientifically agreed threshold values relating to MP ingestion established (DHLGH 2021). *Nephrops norvegicus* has previously been proposed as a species used to monitor MP pollution in the benthic environment (Fossi et al. 2018, Cau et al. 2019, Carreras-Colom et al. 2022a, Joyce et al. 2022a). This decapod crustacean is found in the North East Atlantic and the Mediterranean, from Iceland and Norway in the north to Morocco and Greece in the south, giving it a wide distribution across Europe (Rice and Chapman 1971, Johnson et al. 2013). They are territorial organisms mainly found in muddy sedimentary environments, where they make short trips to forage and mate (Chapman and Rice 1971, Johnson et al. 2013). Found along the continental shelves and slopes, between 10 and 800 m in depth, they have a life expectancy of 5 – 10 years (Hill, 2008, Johnson et al. 2013, Lolas and Vafidis 2021), therefore, having a potential long exposure to MPs over their lifespan and a relatively local representativeness of MP contamination.

This review focuses on the suitability, and limitations associated with the use of *N. norvegicus* for monitoring MP pollution, to provide information for the implementation of a MP monitoring program in respect of the Marine Strategy Framework Directive (EC 2008) and to inform policy makers and any future European or national regulations on MPs. To achieve this the study aims to (i) review the available data on MP ingestion in *N. norvegicus,* (ii) assess the effectiveness of *N. norvegicus* as a monitoring tool for MP pollution, and (iii) assess its suitability to achieve the aims of an appropriate monitoring tool. Finally, recommendations for future monitoring priorities are presented in relation to sampling and monitoring protocols.

2. Methodology

This review was conducted in February 2023 by retrieving scientific literature from various academic databases including the Web of Science and Google scholar. The search was restricted to peer- reviewed original papers written in English between 2011 and 2023. The following terms, including combinations of them, were used in search databases: (microplastics or microplastic and *Nephrops* or *Nephrops norvegicus* or Norway lobster or Dublin Bay prawn). The criteria for literature selection must include MP pollution in the target species. Lists of references from the research papers were inspected with the aim of finding studies that had not been identified through the search platforms. This review included 11 articles that reflected MP abundances within wild caught *N. norvegicus* across Europe. Research papers comprising of laboratory studies, habitat pollution or review articles were not included in the main review but were discussed when evaluating *N. norvegicus* suitability as a monitoring tool for MP pollution. The suitability of *N. norvegicus* as a monitoring tool for MP pollution was assessed using the six main ecological and biological selection criteria set out by Fossi et al. (2018).

3. European field investigations on MP ingestion in *Nephrops norvegicus*

3.1. *Geographical variation in MP abundance in Nephrops norvegicus across Europe*

N. norvegicus is widely distributed across Europe with stocks divided into Functional Units (FU) and Geographical Subareas (GSA) which are designated fishing grounds based on suitable muddy habitat for the species. The MP abundances in *N. norvegicus* stocks have been investigated in FU's 10, 11, 13, 15, 16, 17, 19, 20–21, 22 and 30 (Welden and Cowie 2016a, Hara et al. 2020, Joyce et al. 2022a) and in GSA's 5, 6, 11, 17 (Cau et al. 2019, Martinelli et al. 2021, Carreras-Colom et al. 2022a) across Europe (Fig. 1).

These results highlight the frequent occurrence of MPs in the decapod crustacean, *N. norvegicus* (Table 1). The MP abundances differ between field investigations, with various MP loadings recorded, potentially reflecting local levels of MPs in the surrounding environment. The occurrence of MPs in *N. norvegicus* varies spatially with 72 % (Joyce et al. 2022a) and 69% (Hara et al. 2020) of organisms recorded as carrying MPs (in their gastro-intestinal tract; GIT) in the North East Atlantic with similar, high MP prevalence levels recorded in Scottish waters, namely 67% (Welden and Cowie 2016a) and 83% (Murray and Cowie 2011) and the Mediterranean Sea, 83% and 100% (Cau et al. 2019, Cau et al. 2020, Martinelli et al. 2021). In contrast, lower levels of MPs have been reported in the decapod crustacean in the Baleric and Adriatic Sea, 38% and 10%, respectively (Avio et al. 2020, Alomar et al. 2020). Recent studies have also identified areas within the geographical range with high MP abundances (e.g., Clyde Sea in Scottish waters, Gulf of Cadiz in the Northeast Atlantic, Western Irish Sea in Irish waters and Barcelona in the NW Mediterranean Sea); see Table1); (Welden and Cowie 2016a, Carreras-Colom et al. 2022a, Joyce et al. 2022a), which suggests an increased risk to marine biota in these areas. However, only one study in the Clyde Sea reported abundance values as items per individual (Carreras-Colom et al. 2022a). The plastic loads recorded by Welden and Cowie (2016a) were in in weight (mg), while not directly comparable, was identified as being greater than those reported by Carreras-Colom et al. (2022a). The average MP abundance recorded varies between studies and sites, ranging from 0.48 to 13.08 items per individual (Table 1), with the highest abundances reported in the Mediterranean and the Clyde Sea (Welden and Cowie 2016a, Cau et al. 2019, Martinelli et al. 2021, Carreras-Colom et al. 2022a) with both these sites described as areas of high MP pollution (Welden and Cowie 2016a, Cózar et al. 2015). The Mediterranean Sea and the Clyde Sea Area are semi-enclosed waterbodies that are in the vicinity of many anthropogenic sources and high human pressure which may be the reasoning for its higher abundance of MPs (Rippeth and Jones 1997, Cózar et al. 2015, Welden and Cowie 2016a). This provides further support for the suitability of *N. norvegicus* as a potential monitoring tool for MP pollution as it displays levels of ingested MPs that reflect the local variation in MP availability (Carreras-Colom et al. 2022a, Joyce et al. 2022a).Table 2..

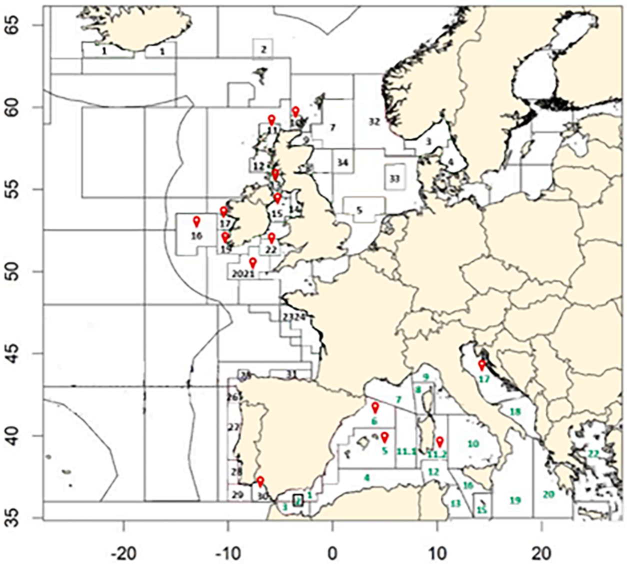

Fig. 1. Nephrops norvegicus distribution across functional units (FUs) in ICES areas (black) and geographical subareas (GSAs) in the Mediterranean (green). Red location icon corresponds to areas where MP abundances in N. norvegicus have been investigated.
Adapted from Dobby et al. (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As well as showing spatial differences, *N. norvegicus* have been recorded as reflecting temporal trends in pollution levels, where in a recent study, both annual and intra year variability was reported (Carreras-Colom et al. 2022a). Organisms sampled in the Ebro Delta showed variations between 2018 and 2019 sampling events, where the mean abundance of MPs was greater in 2019, and specimens from the Clyde Sea, sampled in both May and August of the same year showed a great variation in levels between sampling dates, with a fourfold increase (2.77 and 11.23 MPs per individual, respectively) (Carreras-Colom et al. 2022a). These changes in MP abundances further highlight the ubiquity and heterogeneity of MPs in the marine environment. The levels and movement of MPs in the benthic environment is poorly understood (Barrett et al. 2020, Esposito et al. 2022). It may relate to several complex interactions of ocean dynamics, environmental ability, including proximity to point source and anthropogenic activity, and the biotic and abiotic pathways to sediment and potentially the food chain (Huang et al. 2020, Franceschini et al. 2021, Joyce et al. 2022a). Moreover, wider temporal differences can be inferred through *N. norvegicus* when comparing the MP levels observed in the Clyde Sea from sampling events in 2009, 2011 and 2019 (Murray and Cowie 2011, Welden and Cowie 2016a, Carreras-Colom et al. 2022a). However, the differences of the methodological approach between studies does not allow for a direct comparison, therefore caution must be taken into consideration while interpreting the results.

It has also been suggested that *N. norvegicus* sampled further away from anthropogenic sources demonstrated a lower level of MP pollution (Welden and Cowie 2016a, Joyce et al. 2022a). In a study carried out in Irish waters the site furthest and deepest from shore, the Porcupine Bank (PB), had the lowest level of MPs in *N. norvegicus*, whereas both sediment samples and *N. norvegicus* samples collected in the Western Irish Sea (WIS) showed higher levels of MP pollution in comparison to all other sampling sites (Joyce et al. 2022a). This has been hypothesised as being due to the WIS being in close to highly industrialised coasts, while the PB is more isolated and likely exposed to fewer anthropogenic impacts (Joyce et al. 2022a).

3.2. *Characteristics of MP pollution in Nephrops norvegicus*

Global patterns have identified fibres as being the most dominant MP

Table 1
Literature review summary on microplastic analysis in wild caught *N. norvegicus*. (Methods of examination: A: Alkaline digestion (10% KOH) + µFTIR; B: Visual examination + µFTIR; C: Visual examination + µRAMAN; D: Visual examination; E: Enzymatic digestion + µFTIR; F: Density Separation (NaCl) + µFTIR; G: Density separation + Alkaline digestion + µFTIR; H: Density Separation, + Hydrogen peroxide digestion (H2O2) + µFTIR; n.l.: not listed; n.d.: no data).

Location	Year	N	Method of examination	Abundance items ind^{-1}	% Occurrence	Most common MP type	MP size range (mm)	Most common length (mm)	Max. MPs ind^{-1}	Entanglements reported	Reference
North East Atlantic	2020	600	A	2.20 ± 2.47	72	Fibre	0.045–53.88	<1	19	Yes	(Joyce et al. 2022a)
Western Irish Sea	2020	100	A	3.66	82	Fibre	n.l.	n.l.	16	nl	
Porcupine Bank	2020	100	A	0.8	42	Fibre	n.l.	n.l.	7	nl	
Aran Prawn Grounds	2020	100	A	2.31	84	Fibre	n.l.	n.l.	13	nl	
SE and SW Coasts of Ireland	2020	100	A	2.15	77	Fibre	n.l.	n.l.	8	nl	
Labadie Jones and Cockburn	2020	100	A	1.56	64	Fibre	n.l.	n.l.	19	nl	
The Smalls	2020	100	A	2.74	81	Fibre	n.l.	n.l.	11	nl	
Clyde Sea, Gulf of Cadiz and Baleric Sea	2007–2019	204	B	7.60 ± 12.01	77.8	Fibre	0.1–44.7	1–2	75	Yes	(Carreras-Colom et al. 2022a)
Clyde Sea	2019	60	B	7.00 ± 11.90	n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
Gulf of Cadiz	2017	24	B	13.08 ± 13.49	n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
Costa Brava	2019	20	B	6.20 ± 6.80	n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
	2018	20	B	2.50 ± 2.50	n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
Barcelona	2019	20	B	12.55 ± 20.78	n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
	2018	20	B	10.40 ± 14.08	n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
	2007	20	B		n.l.	Fibre	n.l.	n.l.	n.l.	Yes	
				9.40 ± 13.36							
Ebro Delta	2019	20	B	5.20 ± 4.44	n.l.	Fibre	n.l.	n.l.	n.l.	No	
	2018	20	B	2.15 ± 2.76	n.l.	Fibre	n.l.	n.l.	n.l.	No	
Adriatic Sea	2019	23	E	4.9 ± 2.4	100	Fragments	0.051–0.431	x̄ ~ 0.145	23	No	(Martinelli et al. 2021)
Sardinian waters, Mediterranean Sea	nl	27	F	2.1 ± 0.6 MPs and 3.9 ± 0.5 MPs in stomachs and intestines	100	Fragments	0.2–1	n.l.	13	No	(Cau et al. 2020)
Sardinian waters, Mediterranean Sea	2017	89	G	5.5 ± 0.8	83	Films	0.1–5	< 0.5	42	No	(Cau et al. 2019)
Galway Bay West Coast of Ireland	2017	32	A	0.48	nl	Fibre	n.l.	n.l.	n.l.	No	(Pagter et al. 2020a)
Irish Waters	2016	150	A	1.75 ± 2.01	69	Fibre	0.143–16.976	1–2	10	Yes	(Hara et al. 2020)
Aran Prawn Grounds	2016	30	A	0.9 ± 1.03	56.7	Fibre	n.l.	n.l.	4	n.l.	
Bantry Bay	2016	30	A	1.67 ± 2.0	73.3	Fibre	n.l.	n.l.	10	n.l.	
Kenmare Bay	2016	30	A	2.3 ± 2.47	70	Fibre	n.l.	n.l.	10	Yes	
Magharees Union	2016	30	A	1.67 ± 1.9	60	Fibre	n.l.	n.l.	7	n.l.	
North Irish Sea	2016	30	A	2.20 ± 2.2	83.3	Fibre	n.l.	n.l.	9	n.l.	
Adriatic Sea	2016	10	H	1 ± 0	10	Fibre	n.l.	n.l.	n.l.	No	(Avio et al. 2020)
Balearic Islands	2015	8	D	0.63 ± 0.32	38	Fibre	n.l.	n.l.	n.l.	No	(Alomar et al., 2020)
Scottish waters	2011	1450	B	n.d.	67	Fibre	n.l.	n.l.	n.l.	Yes	(Welden and Cowie 2016a)
Clyde Sea Area	2011	1000	B	n.d.	84.1	Fibre	n.l.	n.l.	n.l.	Yes	
North Minch	2011	150	B	n.d.	43	Fibre	n.l.	n.l.	n.l.	Yes	
North Sea	2011	300	B	n.d.	28.7	Fibre	n.l.	n.l.	n.l.	Yes	
Clyde Sea; Isles of Cumbrae	2009	120	C	n.d.	83	Fibre	n.l.	n.l.	n.l.	Yes	(Murray and Cowie 2011)

Table 2

Microplastic exposure experiments in *Nephrops norvegicus* (Exposure type: a: acute/single exposure, b: chronic/continuous exposure (3 times a week for 3 weeks), c: chronic/continuous exposure over 8 months (360 MPs over experimental period).

Type/ shape	Polymer	Sizes	Concentrations	Exposure time	Reference
fibre	Polyester (virgin)	3, 5, 10 mm	5 MPs / 1 g of fish ^{a}	0 – 168 h	(Joyce et al. 2022a)
beads	Polyethylene, polystyrene (virgin and PCB loaded)	6, 500–600 µm	155 mg microspheres per gelatin cube ^{b}	3 weeks	(Devriese et al. 2017)
fibre	Polypropylene (virgin)	3–5 mm	5 filaments / 1.5 g food ^{c}	8 months	(Welden and Cowie 2016b)
fibre	Polypropylene (weathered)	5 mm	10 filaments /1 cm^{3} of fish ^{a}	24 h	(Murray and Cowie 2011)

type in the marine environment and the most observed MP type in *N. norvegicus* (Hara et al. 2020, Rebelein et al. 2021, Carreras-Colom et al. 2022), with fibres reported to be the most dominant in eight out of the eleven reviewed articles. There are however contrasting studies, that targeted MP ingestion by *N. norvegicus* in the Mediterranean and have reported a predominance of fragments and films over fibres (Cau et al. 2019, Cau et al. 2020, Martinelli et al. 2021). Nevertheless, MP fibres were still present in samples from the Adriatic Sea Study (26.8%) but were less predominant than fragments (73.2%) (Martinelli et al. 2021). Furthermore, Cau et al. (2019) retrieved fibres in his *N. norvegicus* samples, however, excluded > 1700 fibres from their results due to potential contamination (Cau et al. 2019). The inconsistency in findings of MP types in the Mediterranean Sea is thought to be related to different methodological practices rather than differences in the environment (Carreras-Colom et al. 2022b). Other crustaceans have reported a dominance of MP fibres which may reflect their ability to be easily ingested and potentially be retained for longer than other MP types (Villagran et al. 2020, Yin et al. 2022).

The entanglements of fibres, which are thought to aggregate during the intermoult period, were reported in six out of the 11 field investigations (Table 1). These have been highlighted as a concern, due to their possibility of causing blockages and false satiation in organisms (Welden and Cowie 2016b). Furthermore, a recent study found a correlation between high levels of MPs and the presence of entangled balls within *N. norvegicus* (Carreras-Colom et al. 2022a). Welden and Cowie (2016a), stated that organisms from the North Sea and the Minch had lower levels of MP pollution and were mainly comprised of single strands of fibres in comparison to the Clyde Sea area which had a higher abundance of MPs and entanglements. This supports the hypothesis that the low prominence of entanglement, for example, those reported in the North East Atlantic (Joyce et al. 2022a), may reflect a low level of MP pollution in comparison to areas of high plastic pollution such as the Mediterranean. From the literature reviewed, the most dominant pollutants retrieved from the GIT of *N. norvegicus* were < 2 mm, with larger fibres less abundant in the GIT of *N. norvegicus* (Cau et al. 2019, Carreras-Colom et al. 2022a, Joyce et al. 2022a). In one study conducted in Irish waters only 2.6% of the MP fibres retrieved from *N. norvegicus* were > 5 mm in length (Joyce et al. 2022a), and in Sardinian waters approximately 1% of particles were identified as being > 5 mm (Cau et al. 2019).

In the waters around the Irish coast, blue was the most common colour of MP reported (Hara et al. 2020, Pagter et al. 2020a, Joyce et al. 2022a) and in the Mediterranean and the Clyde Sea white/transparent MP particles were recorded as the most prevalent (Murray and Cowie 2011, Cau et al. 2020, Carreras-Colom et al. 2022a). However, a range of colours were reported in *N. norvegicus* across its distribution including black, grey, red, green, yellow, brown, purple, orange, pink and multi-coloured (Murray and Cowie 2011, Cau et al. 2020, Hara et al. 2020, Carreras-Colom et al. 2022a, Joyce et al. 2022a). The most reported polymers retrieved from *N. norvegicus* from previous research include polyethylene (PE), polypropylene (PP), polyamide (PA), polyester (PES), polystyrene (PS), polyvinyl chloride (PVC) and polyacrylonitrile (PAN). The links between MP colour or even polymer characterisation and anthropogenic uses are difficult to establish, and the dominant polymers or colours can be potentially attributed to a wide range of sources (Carr 2017). Nevertheless, the potential sources and pathways of MPs across *N. norvegicus* distribution are hypothesised in many studies for example, PS, used for food packaging, electrical equipment, inner fridge liner (Plastics Europe 2019) and used in the fishing and aquaculture industry (EUNOMIA 2018) was recorded from *N. norvegicus* by (Hara et al. 2020, Joyce et al. 2022a), around the coast of Ireland. A recent study found that the northern Irish Sea had the highest number of polymers identified around the coasts of Ireland (Hara et al. 2020), which may be due to its position between the two highly industrialised coasts. In Sardinian waters several different polymers were retrieved, e.g., PP, PE, PS and PA, and these were suggested to be derived from packaging materials and textiles due to the polymeric composition, shape and colour (Cau et al. 2019, Cau et al. 2020). In one study from Sardinia the polymer characterisation was looked at separately in the GIT compartments and a significant difference was found both in size and polymeric composition between particles isolated from the stomach and the intestine, with a greater variety of polymers retrieved in the intestine (Cau et al. 2020). In the Adriatic Sea within a semi-enclosed basin, GSA 17, the most common polymers, i.e., PES, PA, PE and PVC (Martinelli et al. 2021) are hypothesised to be from many types of plastic litter including food packaging, bags, bottles and from fishing nets and mussel nets due to the high incidence of fishing activity in the area (Martinelli et al. 2021). PA and PP were found to be the most abundant polymers retrieved in studies from both 2016 and 2019 in the Clyde Sea Area (Welden and Cowie 2016a, Carreras-Colom et al. 2022a), similar to the polymers identified in the Gulf of Cadiz with the inclusion of PES (Carreras-Colom et al. 2022a) which are common polymers used in fishing practices (EUNOMIA 2018, Stanica-Ezeanu and Matei 2021). In the Balearic Sea, PES was the most common polymer retrieved (Carreras-Colom et al. 2022a) which is one of the most widely used materials for food packaging, water bottles, soft drinks, juices, and cleaners in addition to clothing (Sillanpää and Sainio 2017, Plastics Europe 2021, Stanica-Ezeanu and Matei 2021).

MP fibres are usually assumed to be of synthetic origin, however, natural fibres made from wool, linen, and cotton are also found in the marine environment (Remy et al. 2015, Sanchez-Vidal et al. 2018, Pagter et al. 2020a). The importance of using a secondary form of identifying MPs such as FTIR was highlighted by Pagter et al. (2020) as approximately 20% of the MPs retrieved their study were identified as natural. Although the percentage of natural fibres reported in *N. norvegicus* in this review was relatively low (Carreras-Colom et al. 2022a, Joyce et al. 2022a), the "natural" fibres present in the marine environment often contain chemical dyes and other additives like other MP particles making them potentially hazardous (Ladewig et al. 2015, Stanton et al. 2019, Le Guen et al. 2020). Additionally, these natural fibres are not naturally present in the marine environment and therefore are in fact an anthropogenic contaminant. Little attention is given to natural fibres in the marine environment (Stanton et al. 2019), however, they should be reported and monitored along with other MP pollution due to their potential to contain chemical pollutants (Ladewig et al. 2015, Athey and Erdle 2022). Particularly when considering that almost

80% of the microfibers retrieved from surface waters were identified as cellulosic (Suaria et al. 2020).

3.3. Biological parameters influencing MP pollution in N. Norvegicus

The relationship between MP abundances in *N. norvegicus* and their biological parameters have been previously assessed with contradictory findings between studies. Larger organisms have been reported to have a lower abundance of MPs recorded in three studies investigating their relationship (Murray and Cowie 2011, Welden and Cowie 2016a, Joyce et al. 2022a) however, these results are in contrast to findings by Hara et al. (2020) where the highest abundance of MPs were recorded in larger organisms. Nevertheless, it has been hypothesised that as *N. norvegicus* grows, in turn so does its gastric mill, allowing for the larger organisms to potentially egest more MPs in comparison to smaller organisms (Welden et al. 2015, Welden and Cowie 2016a). The moult stage of *N. norvegicus* has also been hypothesised as having an influence on MP abundance (Murray and Cowie 2011, Welden and Cowie 2016a, Carreras-Colom et al. 2022a). The process of moulting has been previously identified as a key route of removing MPs in the stomach of *N. norvegicus*, as lower levels of fibres were recorded in organisms that had recently moulted and MP fibres were also identified in the discarded gut lining of moulted individuals (Welden and Cowie 2016a). In the Gulf of Cadiz, a significantly reduced occurrence of fibres and mean abundance of fibres were seen in individuals at the post moult stage in comparison to those at intermoult (Carreras-Colom et al. 2022a). However, other studies investigating this relationship found no association between MP abundance and moult stages (Hara et al. 2020, Joyce et al. 2022a). A trend was seen between MP abundance and sex in the North-East Atlantic ($R_s = 0.105$) (Joyce et al. 2022a) and a heavier amount of plastic was also found in the stomach of female organisms in comparison to males in Scottish waters (Welden and Cowie 2016a). The link between individual size and MP abundance may also be the reason for the relationship seen between sex and MP abundance due to moulting frequencies being lower in females than males, thus leading to bigger gastric mills in the latter (Welden and Cowie 2016a). Furthermore, the presence of the parasitic dinoflagellate *Hematodinium* spp. showed no significant correlation with MP abundance (Joyce et al. 2022a). Similarly, no relationships were established between the presence of MP and the diet composition (Carreras-Colom et al. 2022a); nor with the individual's health condition, assessed through condition indices, enzymatic responses, and histology (Carreras-Colom et al. 2022b). Overall, it is hypothesised that no one individual parameter can be directly linked to MP abundance due to many confounding variables (Lusher et al. 2017, Vendel et al. 2017, Joyce et al. 2022a).

The anatomical compartments from which MPs are extracted can also play a role in the number of MPs retrieved. Most of the literature to date focuses on the presence of MPs in the stomach and/or intestine of *N. norvegicus* (Cau et al. 2020, Hara et al. 2020, Carreras-Colom et al. 2022a, Joyce et al. 2022a). One piece of research has looked at the presence of MPs in the edible tissue (tail) of *N. norvegicus*, with particle size fibre lengths ranging from 20 to 78 μm, highlighting the possibility of translocation of smaller plastic particles (Martinelli et al. 2021). However, the behaviour of smaller MP particles and nanoplastics in *N. norvegicus* are largely unknown and therefore more research needs to be carried out to provide further information for seafood security and human consumption.

3.4. Plastic loadings in N. Norvegicus habitat

The levels of MPs available in the surrounding environment fundamentally determines the potential of MPs being ingested by marine biota, either directly or by consuming other organisms in the benthic environment which have already ingested MPs (Carreras-Colom et al. 2022a, Yin et al. 2022). MPs have been reported in both sediment and water samples from commercially important *N. norvegicus* fishing grounds (Welden 2015, Martin et al. 2017, Franceschini et al. 2021, Cunningham et al. 2022, Joyce et al. 2022a). A recent study conducted extensive research on a corresponding investigation of MP abundances in an associated environmental matrix in the NE Atlantic (Joyce et al. 2022a). The research indicated that despite no significant correlation, the MP sizes, colours, types, and polymers recorded in *N. norvegicus* mirrored those found in the surrounding sedimentary environment (Joyce et al. 2022a). Despite the lack of significance between environmental loadings and those found in *N. norvegicus,* the proximity of MP sources has also been recognised as a potential driver of MP ingestion by marine organisms (Franceschini et al. 2021). Furthermore, another study carried out in the Clyde Sea Area looked at the relationship between environmental MPs and those ingested by *N. norvegicus* (Welden 2015). The MP type and composition of polymers retrieved in *N. norvegicus* reflected those in the sediment, suggesting that MPs may be taken up directly from this compartment (Welden 2015) further demonstrating their ability to reflect the local MP pollution for monitoring purposes. The MPs retrieved from the water samples were far greater and much less comparable to those found in *N. norvegicus* samples (Welden 2015). The uptake of MPs by *N. norvegicus* is still uncertain, however, it is mainly presumed to be passive from the sediment due to grains being found in their stomachs (Murray and Cowie 2011) along with many benthic organisms that constitute its diet (Cristo and Cartes 1998, Parslow-Williams et al. 2002). However, it must be noted that bottom water may also be a potential source of uptake due to suspension feeding (Santana Cesar Augusto da et al. 2020), as suggested in the NW Mediterranean Sea given the concurring presence of long MP fibres in near-bottom waters and stomach contents of *N. norvegicus* and their very low abundances in sediments (Carreras-Colom et al. 2022b). The role of confusion of prey or trophic transfer may also be involved (Farrell and Nelson 2013, de Sá et al. 2015).

Along with the uptake of MPs being unknown, the presence of MPs retrieved from water and sediment samples is likely to fluctuate between sites/times of year (Sanchez-Vidal et al. 2018, Schmidt et al. 2018). Seasonal distribution of MPs in surface waters and sediments have been previously shown to have an inverse correlation; one high as the other is low (James et al. 2021). The abundance of MPs in surface waters was highest when the sea state was high as MPs were suspended in the water column whereas the highest abundance was recorded in the sediment during calm sea conditions, reflecting a lower sea state, when MPs settled (James et al. 2021). The spatial distribution of MPs is also controlled by ocean currents, wind patterns and extreme weather events and can play a major role in the suspension and resuspension of MPs in the marine environment (Hitchcock 2020, Kane Ian et al. 2020).

3.5. Laboratory exposure experiments of MPs in N. Norvegicus

Laboratory exposure experiments play an important role in understanding the potential adverse effects of MP exposure to marine biota through ingestion (Murray and Cowie 2011, Watts et al. 2014, Welden and Cowie 2016b, Hankins et al. 2018, Rebelein et al. 2021). However, studies on MP ingestion often report contradictory results. *N. norvegicus* has been previously used in laboratory exposure experiments to assess the uptake, retention, accumulation, and egestion of MPs (Murray and Cowie 2011, Welden and Cowie 2016b, Devriese et al. 2017, Joyce et al. 2022b). As non-selective feeders, no differentiation between food and food seeded with MPs (beads or fibres) has been recorded in a laboratory setting (Devriese et al. 2017, Joyce et al. 2022b).

Murray and Cowie (2011) were the first study to demonstrate the ingestion and retention of MP fibres in *N. norvegicus*. The short-term laboratory study used 20 organisms, 10 of which were fed five 5 mm PP fibres seeded within fish. After 24 hrs all organisms were shown to contain MP fibres within their stomachs illustrating the possibility that MP fibres traverse at a slower rate through the GIT than natural food items which have been shown to be egested within a 24 h time frame (Sardà and Valladares 1990, Murray and Cowie 2011, Joyce et al.

2022b). This longer retention time of MPs in comparison to natural food items therefore may be due to blockages in the GIT consequently threatening the organism's fitness. Additionally, impacts of MPs alone or in combination with toxic chemicals such as Polychlorinated Biphenyls (PCBs) have been investigated in *N. norvegicus* (Devriese et al. 2017). Another short-term exposure trial focused on the effects of both virgin and PCB loaded microbeads (6–600 µm) over 3 weeks; the beads were seen to have no impact on the nutritional state of *N. norvegicus.* In contrast, a long-term exposure trial carried out on 36 individuals, in which 12 organisms were fed 3–5 mm PP fibres every two days over an 8-month period revealed a decrease in the nutritional state and a reduction in the feeding rate (Welden and Cowie 2016b). Similarly in a recent exposure study on planktivorous damselfish, *Pomacentrus amboinensis,* MP fibres were egested at a slower rate than MP particles (Santana et al. 2021). This highlights the potential of fibres to pose a greater risk to individuals, as they can potentially become entrapped in the GIT in comparison to beads which are spherical and therefore may be easily egested (Au et al. 2015, Yu et al. 2021). These finding corroborate the amplified reporting of MP fibres in comparison to particles in many aquatic organisms and highlights the need for more research on the potential adverse effects of MP fibres to aquatic organisms (Santana et al. 2021).

A recent exposure trial carried out by Joyce et al. (2022b) determined the size dependent egestion on polyester MP fibres of different lengths and found that smaller fibres of 3 mm were egested within 24 hrs. However, larger fibres of 5 and 10 mm were retained for longer, presumably as fibres of this size are too large to immediately pass-through the complex digestive tract of *N. norvegicus*. In a study carried out by Cau et al. (2020) larger MPs were found in the stomachs of *N. norvegicus* with smaller ones found in the intestine showing the potential for the stomach to retain larger MP particles. This is similar to findings by Carreras-Colom et al. (2022) where longer fibres were more dominant in entanglements found in the stomach of wild caught *N. norvegicus*. The research suggests that larger fibres might be retained for a longer period and are more likely to become entangled, however, they are not believed to accumulate over their entire life. In previous studies, the larger (presumed to be older) organisms did not have a higher abundance of MPs in comparison to smaller individuals (Murray and Cowie 2011, Welden and Cowie 2016a, Carreras-Colom et al. 2022a, Joyce et al. 2022a). Overall, there are contradictory findings between studies which are likely due to the differences between MP types, sizes, concentrations, polymer type and therefore do not allow for a direct comparison. Moreover, it has been hypothesised that MP particles are either eventually egested, fragmented, or removed through ecdysis (Welden and Cowie 2016a, Cau et al. 2020, Joyce et al. 2022a). These results suggest that *N. norvegicus* are most effective at monitoring MP particles < 3 mm which are thought to provide a snapshot of recent MP pollution and are the most reported MP sizes in *N. norvegicus* (Cau et al. 2019, Hara et al. 2020, Carreras-Colom et al. 2022a, Joyce et al. 2022a). However, they potentially can retain and/or entangle fibres of greater lengths when present at high abundances, potentially giving a false representation of the bioavailable MPs with more research needed to understand the retention of MP fibres. The true effects and the contamination thresholds at which MPs are harming the health of many marine organisms, at both an individual and ecosystem level is still relatively unknown.

4. *Nephrops norvegicus* and its potential use as a monitoring tool for microplastic pollution

The ongoing monitoring practices for MP pollution are limited especially in terms of their distribution and temporal trends. The lack of data especially in open oceans and remote areas are required to form baselines and understand the long-term trends and effects of MP pollution. The assessment of MPs in the marine environment has been increasing with particular interest given to the commercially important seafood species *N. norvegicus* in recent years (Cau et al. 2019, Hara et al. 2020, Martinelli et al. 2021, Carreras-Colom et al. 2022a, Joyce et al. 2022a). This section seeks to determine the advantages and limitations of *N. norvegicus* as a monitoring tool for MP pollution in deciphering its eligibility to be used in future monitoring programmes.

4.1. Advantages of using Nephrops norvegicus as a bioindicator species

The characteristics outlined in Table 3 support the use of *N. norvegicus* as an indicator species for the monitoring of MP pollution. *N. norvegicus* are relatively sessile organisms, making them a suitable indicator of local MP pollution in other matrices (e.g., sediment) (Kershaw et al. 2019, Carreras-Colom et al. 2022a), providing clear spatial and temporal gradients. They are a commercially valuable seafood species with landings worth approximately €287 million in European waters in 2018 (Eumofa 2020). In areas of high seafood consumption in Europe, 11,000 MP particles are estimated to be ingested by humans annually (Van Cauwenberghe and Janssen 2014); therefore, they play a valuable role in assessing the potential link to human health effects. Moreover, no effects of the ingestion of MPs have been assessed to date in terms of human health impact. Organisms that are consumed whole with their GIT intact pose a greater risk of MP transfer to humans in comparison to *N. norvegicus* as the digestive tract is usually removed prior to consumption. However, this is not always the case, in some circumstances the organism is consumed with the intestine present (pers. obs.) representing an exposure pathway to humans (Smith et al. 2018). The non-edible stomach in decapod crustaceans is suggested to be the main area of MP retention (Yin et al. 2022). Nonetheless, these organisms can still be used for monitoring purposes from a human health perspective regardless of GIT presence (Kershaw et al. 2019).

N. norvegicus are opportunistic scavengers positioned at mid trophic level and found at various depths (10–800 m) in muddy benthic environments (Lolas and Vafidis 2021). This non-selective feeding behaviour and its position in the food chain are potential reasons for MP ingestion by this species (Murray and Cowie 2011, Walkinshaw et al. 2020). A recent study investigating the abundance of MPs in two crustaceans, *N. norvegicus* and *Aristeus antennatus,* reported that *N. norvegicus* had a higher abundance of MPs which was likely due to their feeding behaviour (Cau et al. 2019). Furthermore, their wide geographical and depth distribution allow for comparison between areas across their distribution (Carreras-Colom et al. 2022a). Although no significant relationship between MP levels in *N. norvegicus* and the surrounding sediment has been identified to date (Murray and Cowie 2011, Martinelli et al. 2021, Joyce et al. 2022a), MP characteristics in the species and sediment have been found to be similar (Welden 2015, Joyce et al. 2022a). Moreover, diets of *N. norvegicus* have also been found to reflect those available in the surrounding foraging area (Parslow-Williams et al. 2002). These decapods are easily accessible in terms of sampling effort, from routine sampling or fishing practices and are practical for MP analysis in a laboratory setting due to their small size making assessment feasible and cost-effective (Kershaw et al. 2019, Novillo et al. 2020). This illustrates the species suitability to give a qualitative status on the presence or absence of MPs in the surrounding environment.

4.2. Limitations of using Nephrops norvegicus as a bioindicator species

Like all management tools, there are limitations associated with using *N. norvegicus* alone as a method of monitoring MP pollution. There are still knowledge gaps to be addressed such as a more complete understanding of the retention times of MPs of different sizes, shapes, and polymers. The retention time of different sized MPs was investigated by Joyce et al. (2022b) in *N. norvegicus.* In that work it was proposed that the presence of small MP particles (<3 mm) would represent a snapshot of what was recently consumed, whereas larger MP, particularly > 5 mm, may be retained over long periods. It was hypothesised that larger fibres may become entrapped and even entangled in the GIT,

Table 3
The suitability of N. norvegicus as a monitoring tool for microplastic pollution was assessed using the six main ecological and biological selection criteria set out by Fossi et al. (2018).

Background information	● Common name: Norway lobster, Scampi, Dublin Bay prawn, Langoustine Classification: Decapod crustaceans from the family Nephropidae, sub-family Nephropinae Maximum total length of 25 cm Life expectancy of 5 – 10 years	(Hill, 2008, Ungfors et al. 2013)
Habitat type/ vagility	● Benthic organism Found in muddy environments, on suitable sediment for burrowing Found at depths ranging between 10 and 800 m Rather sessile, territorial organisms, not moving far from their burrows, only leaving to forage and mate.	(Rice and Chapman 1971, Hill, 2008 Ungfors et al. 2013, Welden and Cowie 2016b, Lolas and Vafidis 2021)
Trophic information and feeding behaviour	● Scavenger species Opportunistic predation and suspension-feeding also observed Non-selective feeding behaviour and have been recorded to ingest non-food materials Mid Trophic level	(Santana Cesar Augusto da et al. 2020, Parslow-Williams et al. 2002, Murray and Cowie 2011, Walkinshaw et al. 2020)
Spatial distribution	● Wide distribution, ranging throughout the eastern Atlantic region, from Iceland to Norway to the Atlantic coast of Morocco and in the Mediterranean (Fig. 1)	(Ungfors et al. 2013, Martinelli et al. 2021, Joyce et al. 2022a)
Commercial importance and conservation status	● In 2010, the total landings (European fisheries) were 66,500 tonnes. The consumption of *N. norvegicus* is recorded in many geographical locations Commercially valuable	(Ungfors et al. 2013)
Documented ingestion of marine litter	● MPs have been recorded in *N. norvegicus* from different geographical locations Retention experiments of microplastics carried out Adverse effects reported in experimental exposures	(Murray and Cowie 2011, Welden and Cowie 2016b, Cau et al. 2019, Cau et al. 2020, Hara et al. 2020, Martinelli et al. 2021, Carreras-Colom et al. 2022a)
Others	● Easy to collect due to ongoing monitoring and commercial exploitation of stocks – opportunistic sampling Human consumption - valuable role in MP and associated contaminants transfer from seafood into the food chain Similar types, colour and sizes of MPs retrieved from both *N. norvegicus* and surrounding sediment	(Joyce et al. 2022a, Hara et al. 2020)

particularly in the presence of high abundances of MPs. In this case and considering ecdysis as the main route of MP removal, the load of larger MP could potentially reflect the common moult period, i.e., 6 months for males and 12 months for females. Other processes such as fragmentation mediated by the digestion activity and/or egestion, whose time frame is unknown, might also play a significant role (Welden and Cowie 2016a, Cau et al. 2020, Joyce et al. 2022b). Therefore, in areas mainly compromised of smaller MP fibres, fragments or beads it is possible that they will be egested through faeces at a faster rate representing what is currently available in the environment to the organism. However, in terms of areas with larger MP fibres present, these may aggregate in the stomach of *N. norvegicus* and become trapped for an unknown period potentially giving a false representation of the levels of MPs currently available in the area. The retention time and harm caused to organisms is not determined during monitoring programmes/field investigations, therefore laboratory studies will need to be conducted to better understand the potential effects of MPs and strengthen the role of *N. norvegicus* as a monitoring tool.

The species possesses many benefits of a good indicator species, however, there are many knowledge gaps still present, especially around its interactions with the surrounding seafloor sediment and bottom water. In addition to this, there may be different interactions taking place between different shaped and sized polymers. Although quantitative information is not yet possible due to many confounding environmental variables within the FUs and GSAs, the authors recommend the species as a monitoring tool to give potential qualitative information on the status of the marine environment.

5. Outlook and future recommendations for monitoring microplastics

In recent years, the interest in MP pollution in aquatic organisms and ecosystems has increased exponentially with various concentrations reported from around the globe. Based on the research presented in this review, the authors recommend a twofold approach as suggested by Joyce et al. (2022), with *N. norvegicus* in combination with sediment to be adopted as a monitoring tool for MP pollution. Due to the limitations presented earlier, *N. norvegicus* alone cannot yet provide adequate quantitative information on MP pollution levels in the marine environment. However, it can represent the invertebrate counterpart to the currently established species to monitor MP pollution (i.e., *Fulmarus gracilis*, *Caretta caretta*). Moreover, *N. norvegicus* occupies a mid-trophic level which represents a key position on the trophic chain from an ecological perspective. In addition, the ingestion of MPs by *N. norvegicus* is representative of litter composition in the benthic environment that is available for other benthic species and can be used to investigate the potential adverse effects of ingesting these contaminants of emerging concern. *N. norvegicus* therefore not only monitor the presence of MPs but may also reflect specific ecological consequences for other organisms and provide information on potential human consumption.

The presence of entanglements of fibres in the stomachs of *N. norvegicus* has been proposed as a method for MP monitoring (Carreras-Colom et al. 2022a) and observations could be included as an element in a monitoring protocol. Although this visual examination is rapid and relatively cheap, other studies carried out on *N. norvegicus* in Sardinian waters found an average of 5.5 ± 0.8 MPs, mainly films and fragments, per positive individual (Cau et al. 2019). In a scenario like this, focusing solely on entanglements would be insufficient and lead to the underestimation of the MP levels present. Not to mention that recording the presence of entanglements alone represents an overly simplified characterization of the characteristics of the MP present, which have been thoroughly reported in the species as showing a variety of shapes, sizes, and polymer compositions. Therefore, the use of entanglements as an indicator may be useful in certain geographical regions where longer MP fibres dominate, but it should be coupled to detailed characterizations of the MP in the species in order to properly evaluate the level of MP pollution.

The authors recommend a minimum reporting requirement for the species as highlighted in Joyce et al. (2022c) for example, the MP characteristics including size, shape, colour, polymer characterization along with reported values such as the mean abundance and size ranges of MPs. Nevertheless, the reporting approach may be dependent on the species and specific anatomical compartment being analyzed, therefore it is important to follow reporting requirements in accordance with the latest published guidelines/recommendations. Due to the nature of the opportunistic sampling, seasonal variation and the likelihood of a commercial catch being used, the authors suggest that all factors should be recorded, including sex, size, and moult stage with the aim of potentially covering as many factors that may be influencing ingestion and retention as possible.

Another of the environmental matrices that has been widely studied in recent decades is sediment, (Osterkamp et al. 1998, Power and Chapman 2018, OSPAR 2022d). Sediment collection is currently in place in serval monitoring programmes across Europe e.g., the status and trends in the concentrations of PAHs, PCBs and PBDEs in sediments (OSPAR 2022d), along with the commencement of baseline monitoring of sediments for MP analysis (Maes et al. 2017, Marques Mendes et al. 2021). Marine sediments have been identified as major sinks for plastic pollution (Woodall et al. 2014, Bergmann et al. 2017, Matsuguma et al. 2017). Nevertheless, there is a lack of MP sediment monitoring to date (Pagter et al. 2020b, Marques Mendes et al. 2021). MPs have been recorded in intertidal, subtidal, and deep-sea sediment (Bergmann et al. 2017, Wang et al. 2019, Alvarez-Zeferino et al. 2020). MPs have also been detected in sediments of *N. norvegicus* fishing grounds (Welden 2015, Martin et al. 2017, Franceschini et al. 2021, Cunningham et al. 2022, Joyce et al. 2022a) and therefore, monitoring this environmental matrix in combination with the decapod crustacean would allow for a better understanding of the bioavailable MPs in the environment. The addition of sediment sampling reflecting the large depth range of *N. norvegicus* from coastal to the deep-sea beds will allow for review of MP loadings, comparison to coastal sediments collected outside of these and advance our understanding of potential sources, pathways, and hotspots of MP pollution in the marine environment.

Bottom water has also been suggested as an additional environmental matrix, however, it is not seen as a logistical or economically feasible medium to sample at present in the North East Atlantic, with some FUs at depths $>$ 500 m (e.g., Porcupine Bank) (Joyce et al. 2022a, Soliño et al. 2022). Contrary to sediments, very few studies have focused on this compartment and the knowledge on the proper methodology to use for sampling MPs at such depths is limited. However, the inclusion of bottom water sampling from Mediterranean GSAs and/or shallower coastal embayment's may be a feasible option and provide useful information, now or in the future. The inclusion of a further environmental matrix, such as sediment and/or water, would provide a more ecosystem-based monitoring approach, which has been recommended by researchers (Pagter et al. 2020a, Pagter et al. 2021).

Under the MSFD Commission decision (EU) 2017/848 (COM DEC), threshold values should be decided on a European scale. Threshold values relating to MPs have not been developed to date at a national or regional level (Werner et al. 2020, DHLGH 2021). Werner et al. (2020) stated that to evaluate the status of the environment, the state of a pristine/normal environment is compared to that of an affected one. As a result, reference values must be established against which the existing or potentially changing situation can be evaluated. Threshold values should be set in relation to "harm" level which includes physical damage, toxicological responses, disruption of human activities and socio-economic damages (Werner et al. 2020). Although adverse effects have been observed in *N. norvegicus*, the threshold concentrations of harm or level of risk is unquantified in this species (Welden and Cowie 2016b) and more information is required to determine threshold values for MP abundance in both *N. norvegicus* and benthic sediments. Therefore, the threshold values should be established from pristine/near pristine areas. An established example of this is the OSPAR bioindicator species the Northern fulmar, *Fulmarus glacialis*. The monitoring of this species adopts the precautionary principle, which allows for comparisons to be made by utilizing the least polluted area as a reference point (Werner et al. 2020). The occurrence of MP particles in the GIT of *N. norvegicus* ideally should be zero, as synthetic materials in the marine environment result from anthropogenic activities and are exogenous to benthic habitats. However, accepting that MP particles are present in the environment, a long-term goal for monitoring MP pollution in *N. norvegicus* and the marine environment should be established which reflects this.

5.1. *Challenges with monitoring*

To understand the levels and trends of MP pollution and to draw conclusions, data needs to be comparable from all areas and collated on a regional scale for further exploration. One of the main difficulties faced by policymakers and researchers is the lack of harmonized and standardised methodologies and units of quantification for MP analysis (Vandermeersch et al. 2015, Bonanno and Orlando-Bonaca 2018, Kershaw et al. 2019). Moreover, many researchers have expressed the need for developing and validating these methodologies (Wesch et al. 2016, Hermsen et al. 2018), due to the lack of comparability between studies. Currently there are no scientifically agreed methodologies to monitor the composition, abundance, and spatial distribution of micro-litter (DHLGH 2021). Hence, the monitoring of MPs in marine environment, including *N. norvegicus* and sediment is a major challenge. Many different methods of examination have been carried out to investigate the levels of MPs in *N. norvegicus*, including alkaline digestion, hydrogen peroxide digestion, enzymatic digestion, density separation and visual examination alone (Table 1). The removal of organic matter is recommended for MP examination and quantification in marine organisms (Soliño et al. 2022). Therefore, the authors propose the use of alkaline digestion using potassium hydroxide (10% KOH) at 40 ^{0}C for 48 hr. This has been suggested as being the most efficient solution for digesting gut tissues of *N. norvegicus* without affecting the MP characteristics and has been recommended by many researchers and experts in the field (Bessa et al. 2019, Hara et al. 2020, Joyce et al. 2022a). This methodology reccomended by Hara et al. (2020) has been used in 3/11 studies for the digestion of the GIT of *N. norvegicus* documented in this review (Hara et al. 2020, Pagter et al. 2020a, Joyce et al. 2022a). Nevertheless, the stomach of decapod crustaceans is coated with chitin (Welden et al. 2015) which is resistant to degradation by many chemicals (Roy et al. 2017). Thus, KOH treatment is not enough to fully break down the complex lining in the foregut of these organisms (Hara et al. 2020, Li et al. 2022), requiring additional visual inspection of the filter residue along with the foregut for MP analysis. A recent study on MP extraction from the Banana prawn *Penaeus merguiensis* investigated different methodologies for MP extraction, suggesting that microwave assisted oxidant digestion was the best method for successfully removing chitinous lining along while maintaining the integrity of MPs (Li et al. 2022). Although the standardization of methods is essential for future monitoring purposes, different reagents and protocols may be needed dependent on tissue complexity of different organisms (Soliño et al. 2022). Density separation is the most commonly used method for the extraction of MPs in sediment (Quinn et al. 2017). Various reagents have been used for the extraction of MPs in sediments including sodium chloride (NaCl), sodium iodide (NaI), and zinc chloride ($ZnCl_2$) (Coppock et al. 2017, Ling et al. 2017, Abidli et al. 2018). The use of NaCl, although cheap and environmentally safe, has been linked to a loss of certain high-density polymers. On the contrary $ZnCl_2$, with a higher density (1.6–1.7 g/cm^3), has a high recovery of MPs but is expensive and hazardous to the operator and the environment and Nal is expensive and sensitive to pH (Phuong et al. 2021). Therefore, density separation methods are recommended to be carried out using high density solutions such as Sodium Tungstate Dihydrate ($Na_2WO_4{\cdot}2H_2O$) solution (41% w/

v; 1.4 g/cm^3), a non-toxic, economically viable option suitable for long term monitoring as recommended by Pagter et al. (2018). Nevertheless, it is important to follow methodologies in accordance with the latest published guidelines/recommendations e.g., OSPAR guidelines or any other European policies.

Sampling efforts are another challenging aspect for making comparisons between studies and therefore should be consistent throughout a monitoring programme. To represent a sampling site, a minimum of 50 organisms should be collected to assess the baseline levels of MPs present in *N. norvegicus* following the guidelines set out by the MSFD (Hanke et al. 2013, Hermsen et al. 2018). However, the authors recommend conducting statistical techniques such as a power analysis to determine an appropriate sample size in order to achieve statistically meaningful results with the desired statistical power for long term monitoring. For example, in Joyce et al. (2022a) if power analysis was conducted on the data, it would indicate a sample size of 21 individuals from each site, measured at a power of 90%. A targeted sea undergoing MP monitoring programme would be a sizeable undertaking for relatively small sampling units which may be filled by piggy-backing sampling on other scientific programmes active in the area. Therefore, it is recommended by the authors to carry out monitoring in conjunction with other sampling efforts as they can offer low-cost opportunities for scientific sampling e.g., the Irish Marine Institute fisheries Sampling and Data Collection programme, the Irish Marine Institute Nephrops Under Water Television Surveys and the MEDiterranean International Trawl Survey (MEDITS). Opportunistic sampling is the most feasible option for both *N. norvegicus* and sediment sampling.

Contamination control is another challenging area in terms of monitoring MPs. Despite precautions put in place, preventing contamination in a laboratory setting and for MP exposure studies has been proven difficult with extraneous MPs recovered from experimental organisms in previous research in *N. norvegicus* and other aquatic organisms (Cau et al. 2019, Santana et al. 2021, Joyce et al. 2022b). These findings illustrate the need to report MP contamination and to improve quality assurance and quality control procedures for future MP research and monitoring, in the efforts to elucidate patterns of MP contamination and associated risks in marine organisms (Santana et al. 2021). The contamination quality control for MP analysis in biota should follow the criteria set out by Hermsen et al. (2018) in the efforts to works towards achieving a good quality score.

6. Conclusion

MP pollution in the marine environment is a global crisis that requires a better understanding of the level's, spatiotemporal trends, and accumulation of these contaminants to prevent potential adverse effects in the future. The presence of MP particles in marine crustaceans, including commercially important seafood species, such as *N. norvegicus,* appears to be widespread across their geographical distribution and is a pervasive phenomenon. Monitoring is recommended to be conducted across *N. norvegicus* distribution range, giving a pan-European perspective. Furthermore, the potential ecological and health risks should be assessed to assist in establishing threshold values. This review contributes to D10 of the MSFD in the implementation of a MP monitoring programme using *N. norvegicus* and sediment as potential monitoring tools for MP pollution. Member states are required to establish threshold values for both the abundance of micro litter on the seafloor and levels ingested by marine organism under the MSFD, therefore a long-term monitoring programme is required to determine the trends of MP ingestion for defining these thresholds. Despite *N. norvegicus* and sediment being proposed as a monitoring tool for MP pollution in the benthic environment, the authors recommend a holistic monitoring approach which would include a variety of species and matrices to be used to cover all ecosystem compartments, for a comprehensive MP monitoring programme. The integrated use of *N. norvegicus* and sediment as a monitoring tool is recommended here as being key to monitoring MPs along an extensive spatial scale. In addition, these potential monitoring tools will compliment current and future MP monitoring, incorporating for instance, data from fulmars, coastal sediment, and mussels, to allow for a more robust and cost-effective way to monitor MP pollution in the marine environment.

Declaration of Competing Interest

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

Data availability

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

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