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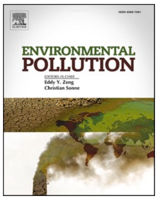

The Ocean Plastic Incubator Chamber (OPIC) system to monitor *in situ* plastic degradation at sea☆

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ABSTRACT

Marine plastic pollution is a global and pervasive environmental issue. Knowledge on plastic degradation in natural settings is still very limited due to current technological limitations, hampering our understanding of plastic fate (including its breakdown into micro- and nanoplastics) and of its risk for marine ecosystems. Here we present the proof of concept of the Ocean Plastic Incubator Chamber (OPIC), a novel equipment to follow plastic degradation *in situ* at sea over time. OPIC consists of a frame containing a motorised rotating stage with transparent tubes sub-assemblies where reference plastic materials are incubated and exposed to natural weathering conditions for defined time multi-years period. OPIC has been designed, tested and adapted for deployment with mooring line platforms in the open ocean with potential future application in remote environments at different depths (from shallow waters to deep sea environments). This incubator will allow us to measure different markers of plastic aging *in situ* in the ocean for the first time, providing new insights into the multiple and locally driven dynamics regulating plastic transformations and fate at sea.

1. Introduction

Plastic pollution is one of the major threats to the environment, affecting marine ecosystems from pole to pole (Villarrubia-gómez et al., 2018). Plastic debris has been documented at every latitude and in every domain, from surface waters to deep sea sediments.

The deep sea (>200 m depth) represents the largest biome on Earth, it provides important ecosystem services, and it houses diverse habitats for unique life forms (Danovaro et al., 2017; Ramirez-Llodra et al., 2010). This vast oceanic compartment is still largely unexplored, although recent evidence suggests that about 99% of all plastic waste lost at sea is estimated to end up in the deep seafloor (Choy et al., 2019). Nevertheless, existing data regarding the occurrence, distribution and transformation of plastic debris in the deep open ocean are still insufficient to model the transport of plastics from the surface to the deep sea (Koelmans et al., 2017).

In the last decade, remotely operated underwater vehicles and towed camera systems have been adopted to monitor the occurrence, distribution and biological interactions of large plastic waste items and abandoned fishing gears in the deep seafloor (Bergmann and Klages, 2012; Bo et al., 2014; Chiba et al., 2018; Tekman et al., 2017). Likewise, oceanic platforms such as moored sediment traps have recently been proposed to measure the temporal sinking rate of microplastics (<5 mm) to the deep ocean (Saarni et al., 2021).

Based on the latest United Nations (UN) World Ocean Assessment report (United Nations, 2021), one of the main knowledge gaps on marine plastic pollution is a clear understanding of plastic degradation in natural environments. Plastic waste undergoes physico-chemical transformations over time, for instance through photodegradation, thermo-oxidation, hydrolysis and biodegradation (Andrady, 2017).

These mechanisms enhance the weathering and aging of plastic polymers at sea, regulating their horizontal and vertical transport (through change in plastic density and size) as well as their availability to biological systems (i.e., biofouling, ingestion in marine biota). Degradation is thus a key aspect affecting the ability of plastic to sink in the water column and distribute and accumulate in the oceanic compartments, from surface waters to the mesopelagic zone and the deep sea (Choy et al., 2019; Cózar et al., 2014; Kvale et al., 2020; Wayman and Niemann, 2021; Welden and Cowie, 2017).

In natural conditions plastic is prone to significant alteration, leading

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to erosion and release of small pieces, classified according to their size as micro- (0.001–5 mm, UNEP, 2021) and nanoplastics (<1 μm, Gigault et al., 2018). The smallest fraction of plastic raise particular concern due to their higher toxic potential to marine wildlife and ecosystems (Corsi et al., 2021, 2020; Villarrubia-gómez et al., 2018). Although detection and quantification are still challenging, nanoplastics have been found in marine waters and sea ice (Materić et al., 2022; Schirinzi et al., 2019; Ter Halle et al., 2017) and micro- and nano-fragmentation from various polymers has been proven in laboratory settings, through thermal cutting (Zhang et al., 2012), exposure to ultraviolet (UV) light (Gigault et al., 2016; Lambert and Wagner, 2016; Mao et al., 2020) and mechanical abrasion (Annenkov et al., 2021).

The study of plastic transformations (i.e., plastic weathering) down to micro- and nanoplastics along the water column is a complex matter due to practical challenges in conducting extensive monitoring studies *in situ*. Laboratory simulations and aging technologies, at relatively short-term scales (days or months, reviewed in Sun et al., 2020), can only mimic some of the multiple environmental factors responsible for the real plastic weathering at sea (Liu et al., 2021). Weathering experiments have suggested that plastic degradation at sea under natural conditions can be accelerated, with significant changes occurring already after 1 year (i.e., Song et al., 2017), also due to the interactions with biological components (Dawson et al., 2018) and microbial communities associated to plastic debris, commonly known as the plastisphere (Roager and Sonnenschein, 2019; Zettler et al., 2013).

For a proper understanding of the mechanisms governing plastic degradation at sea, and in particular in the open ocean and in the deep sea, long-term field-based studies are thus necessary.

To address this knowledge gap, here we describe the prototype of a novel incubator equipment designed and customised for the *in situ* monitoring of plastic degradation at sea, the Ocean Plastic Incubator Chamber (OPIC) system. As in this first study we present OPIC proof of concept, we encourage the use of this equipment for future long-term field-based activities to monitor marine (plastic) pollution and help achieving “a healthy, resilient and clean ocean”, both ambitious targets set within the 2030 Agenda for sustainable development (United Nations, 2015) and the 2021–2030 Ocean Decade activities (United Nations, 2022), respectively.

2. Materials and methods

2.1. OPIC design and construction

The prototype of OPIC system has been designed and assembled at the British Antarctic Survey (BAS, at Cambridge, UK). At top level, OPIC is comprised of three smaller sub-assembles: the external frame, the motor and the sampling equipment, as shown in Fig. 1. The outline of this incubator was inspired by sediment trap technique. Sediment traps are highly efficient systems that collect vertically settling particles in the water column, catching them through a large funnel into individual sample bottles, which are placed on an automated rotating carousel. These instruments have been extensively employed in oceanography over the last 30 years in open ocean for long-term monitoring studies.

OPIC has been conceived with the same kind of stepping motor and carousel, as described below, but with a different function as its containers (sample tubes) are used to expose plastics to natural seawater, instead of collecting material from the water column.

In OPIC, the external frame provides structural rigidity to the incubator assembly, protecting it during transit, deployment, operation and retrieval. The frame portion (as labelled in Fig. 1) consists of a welded frame made from hollow steel bar sections, a steel garage [to shelter samples before/after exposure to the water] attached to a base plate with holes cut in the open half to allow sample exposure to natural environmental conditions.

In the garage area, sample containers are sealed thanks to the friction of the rotating plates (in which sample tubes are placed) against the stationary ones above during rotation allowing long-term storage of the samples.

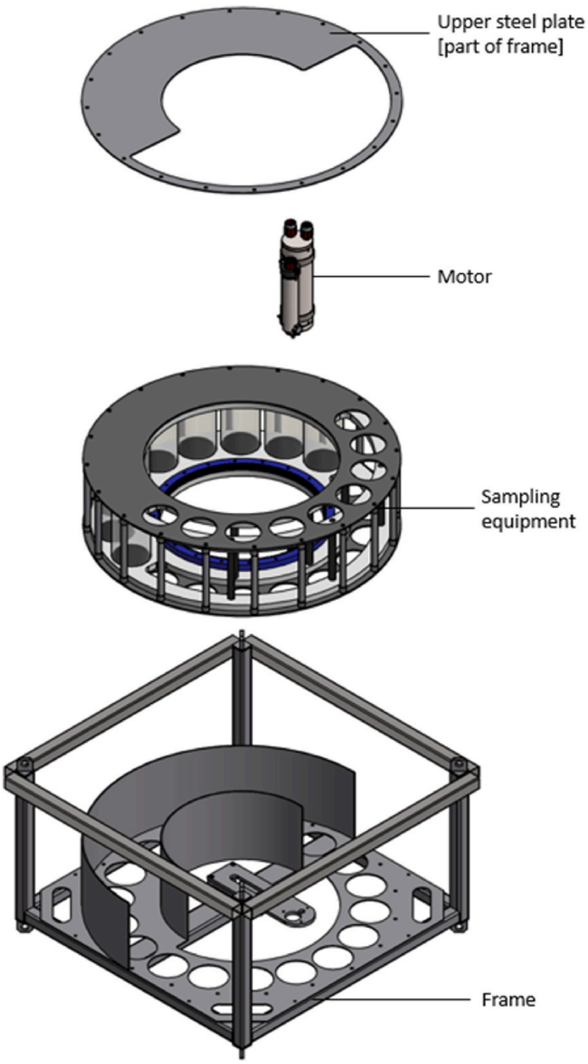

Fig. 1. Top level exploded view of the OPIC assembly (single column image).

This is matched by the top lid to align the sampling equipment, and a motor mount (Fig. 2).

The motor unit was supplied by Hydro-Bios (Germany), one of the main producers for autonomous operating instruments, including sediment traps. This motor has already proven its reliability during numerous long-time operations in changing marine environments, including the Arctic and the Southern Ocean (https://www.hydrobios.de/en/product?product_id=129).

For OPIC prototype, the motor unit was adapted from an existing multi-sediment trap to meet our requirements regarding turning cycles per event and the amount of events it can execute. As for sediment trap techniques, this motor can be programmed to rotate at given intervals to expose samples at different time points. The motor is integrated into the frame assembly, attaching on a central bracket in the frame.

The sampling equipment consists of two pairs of polymer discs [the bearing plate is stationary, and the sample plate rotates], a gear system, support rods with roller bearings, and the sample tube sub-assemblies (Fig. 3). The stationary pair of the polymer discs are bearing plates, which remain fixed to the aforementioned steel discs and provide a surface to seal the samples before they are exposed to the water. The other pair are the sample plates, which hold the sample tubes in compression and rotate to move them out of the garage as required. Both pairs of discs are made from acetal and therefore act as self-lubricating

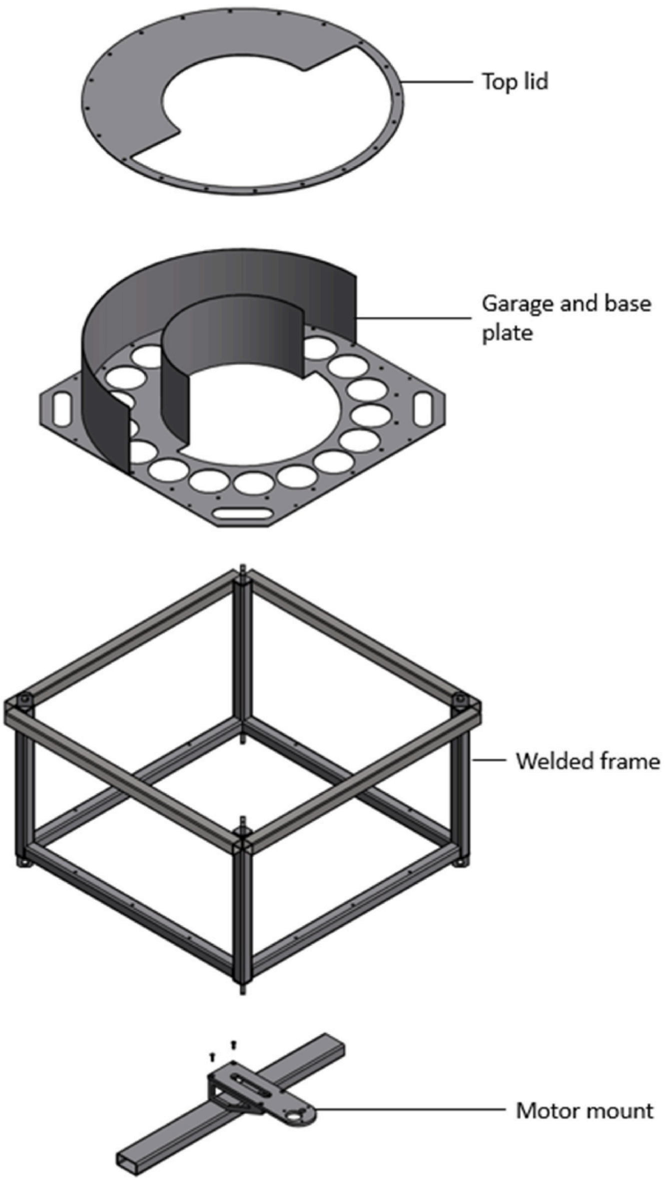

Fig. 2. Exploded view of frame sub-assembly (single column image).

bearings, minimising any friction in the turning of the system. Additionally, the spacers and support rods bear the load between the stationary plates, which have roller bearings attached to facilitate smooth rotation of the moving parts. The gear system is comprised of a spur gear attached to the motor, and a ring gear attached to the lower rotating plate.

The sample tubes (Fig. 4) for plastic incubation are made from acrylic, having a UV transmittance of 92%, to allow UV degradation to occur. The Anodised aluminium end caps with holes in (inner aperture of 1 mm) allow water to flow through the tubes and microbial community to interact with the samples in order to study plastic (bio) degradation. The line drawing (Fig. 4) more clearly shows the holes in the aluminium caps to facilitate the flow of water through the samples and allow any particulate matter or organism larger than 1 mm to escape.

2.2. Overview of the samples examined using OPIC

OPIC is designed to test a variety of plastic materials across a wide range of polymers (with both low and high density), sizes, shapes (fragments, films, textiles) and aging levels (virgin or weathered materials). Examples of plastic samples that can be tested in future applications with OPIC system are shown in Fig. 5 for reference. For each polymer type, a pristine sample can be pre-weathered under laboratory conditions to produce aged samples at different stages of degradation. Aged plastics from environmental samples can be tested as well.

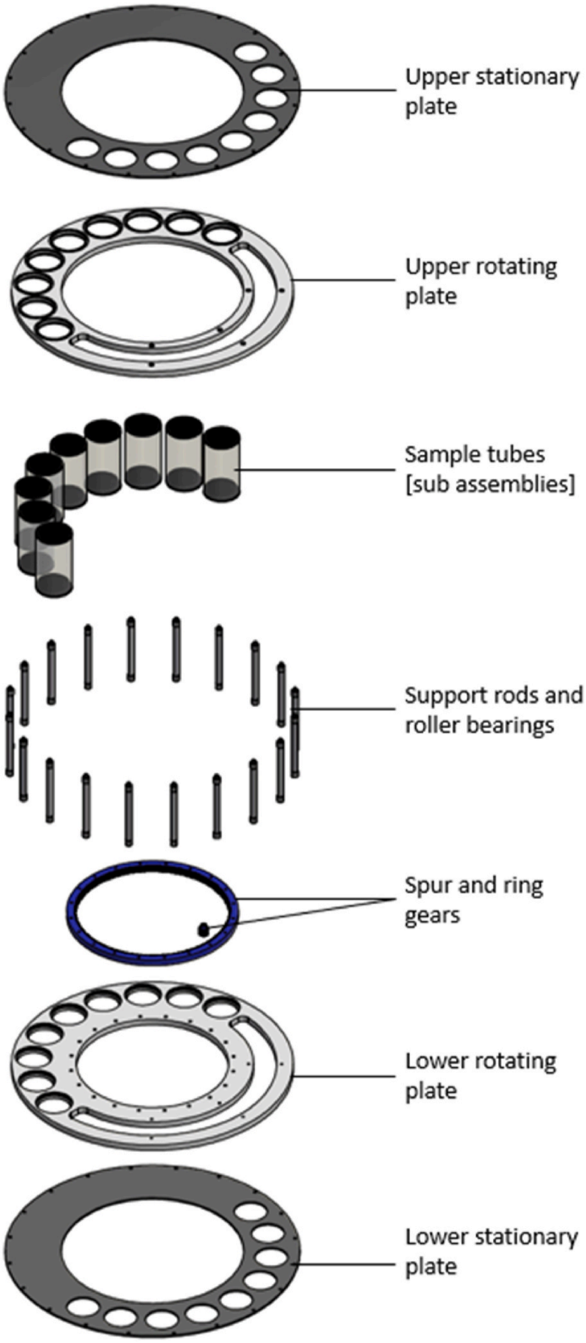

Fig. 3. Exploded view of sampling equipment (single column image).

The Scanning Electron Microscopy (SEM) images in Fig. 5 show the virgin surface of reference polymers (purchased from Goodfellow Cambridge Ltd, UK or obtained from textiles) and the weathered one of plastic polymers after thermal-oxidative treatment (i.e., exposure to 30% Hydrogen Peroxide at 70 °C for 2 weeks). Virgin and weathered plastic pieces were extensively washed in ultra-pure water and imaged using the Hitachi Tabletop SEM TM3000 at BAS laboratory facilities.

Before deployment of OPIC assembly, the properties of the plastic

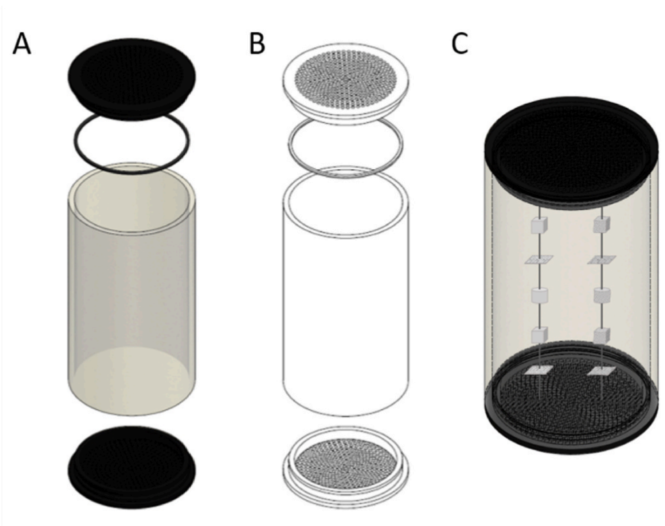

Fig. 4. Sample tube sub-assemblies: (A) exploded view, rendered; (B) exploded view, line drawing; (C) sample tube containing reference plastic pieces and textiles along fishing wires (single column image).

samples, such as plastic density, dry weight, infrared (IR) spectral features and surface roughness, should be characterised as a reference condition before the *in situ* incubation.

In OPIC, the plastic samples can be prepared with a 1 mm hole drilled through the centre in order to be suspended in place within the sample tubes using 0.8 mm fishing wire. The reason for suspension is to minimise mechanical degradation of samples through impact with sides of container. Replicates ($n \geq 3$) of each plastic type can be included in different sample tubes to ensure reproducibility of the exposure conditions at each time point.

Overall, the general characteristics of OPIC prototype are summarised in Table 1.

2.3. *OPIC testing*

The operation of OPIC prototype was evaluated through a bench-scale test and an *in situ* test in natural settings to verify overall stability of the external frame and assemblies during deployment as well as the functioning of the motor unit in terms of programmed response and efficiently rotation of the sampling stage at selected time-points. The bench test was conducted in house at BAS, monitoring the equipment assembly, ease of movement of the parts, and control of the motor.

The *in situ* test was carried out at a local marina (Jones' Boatyard, St

Table 1
General characteristics of the OPIC system.

Dimensions	Total height	590 mm
	Plate diameter	898 mm
	Sample tube inner diameter	100 mm
	Sample tube height	200 mm
Sampling characteristics	Number of samples	14
	Volume of samples	~1 cm^3
	Sampling intervals	up to 9 time-points
Materials	Sample tubes	UV acrylic
	Frame	Stainless steel 316
Weight	In air	100 kg
	In water	74 kg
	Frame	56.5 kg
	Sampling equipment	32.0 kg
Operating depth		Up to 400 m

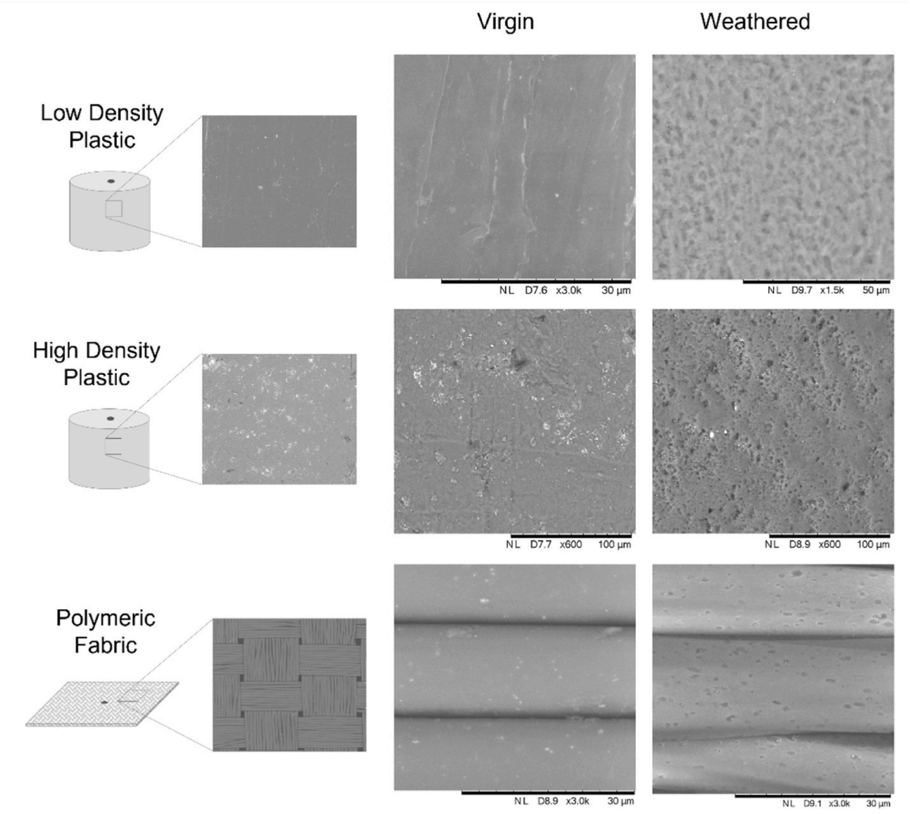

Fig. 5. Examples of plastic samples which could be tested with OPIC. From the top: High Density Polyethylene (HDPE), Polyvinyl Chloride (PVC) and a composite textile of Polyamide and Polyethylene Terephthalate (PA-PET) as examples of low density, high density and fabric polymers, respectively. Scanning Electron Microscopy images show the pristine and laboratory-aged surfaces for each polymer type (2-column image).

Ives, Cambridgeshire). The OPIC assembly was lowered into the water by a fork truck and suspended there for the duration of the test, with an additional camera (GoPro HERO4 Silver) on the frame to capture footage. The equipment was also visible from the surface of the water and so could be monitored by sight. After an initial stationary period of 5 min, the motor was programmed to rotate at 1 min intervals to allow the sample bottles to exit the garage at the selected time points.

3. Results and discussion

3.1. *OPIC operation: results of the test series*

Results from the bench test at BAS (Fig. 6A and B) highlighted required modifications in the motor programming and the geometry of some parts.

Operation of the OPIC system during the *in situ* test (Fig. 6 C) is shown in the Supplementary Material (Video S1), with details of the deployment and rotation of the sampling equipment assembly at 1 min interval to move the sample tubes out of the garage.

The *in situ* test allowed rotation such that 7 of the sample bottles were able to come out of the garage, but the final two did not. Further examination when the assembly was retrieved showed that the gears became unmeshed when the frame was suspended at an angle, as the lower discs and ring gear to shift away from the motor and spur gear. This had not been observed during previous bench-scale testing stages because the assembly had been flat; when it was lifted at an angle the shifting became apparent. The motor plate was consequently replaced with an improved adapted design to provide a better gear fit, and prevent the movement from happening to the extent that the gears would disengage in the future. A further test was then performed to test the newly adapted motor plate in the OPIC assembly, with the results deemed satisfactory for deployment.

Overall, the test series showed proof of concept in OPIC design and functionality of the motor. For its features, this new incubator equipment does not require specific validation and calibration prior usage and can be easily reproduced and employed at sea.

3.2. *Future engineering development*

During initial design stages, a curtain system was designed to block light from entering the garage area. This was intended to protect plastic samples from UV in surface waters, once the samples would have entered the garage following exposure to the surrounding environment for a time defined beforehand.

The curtain parts (Figure S1) are comprised of a long bristle broom head attached to each side of the garage openings, deforming to allow the bottles to pass through and then returning to close the gap. The bristles are made from polybutylene terephthalate. Sections of the bristles are removed to conform to geometry of the equipment. OPIC assembly was not tested with the curtain system in position as first deployment of OPIC will be carried out in the deep sea, but the system is proposed to implement OPIC assembly for future deployment in shallow settings, in which the adequate control of UV exposure provided by OPIC can be relevant to assess the time-series photo-induced degradation of plastic samples.

A specific issue that might occur with OPIC is related to the potential obstruction of the holes in the aluminium cap ends due to possible accumulation of settling organic material/biofilm formation during OPIC long-term deployment.

Other instruments commonly used in oceanography are equipped with a similar netting coverage, for example the SAMI-PH Sensor (https://seacatalog.com/product/sami2-ph/), and, as far as we know, large biofilm formation has never been observed on these instruments in previous long-term monitoring studies.

However, we are aware that this issue might still occur in regions characterised by high primary productivity and carbon export. Different measures to minimise this risk can be undertaken, for example by: (i) choosing a different inner aperture size for the aluminium caps; (ii) selecting time periods for the exposure of the sample tubes taking into account the seasonal concentration of organic matter in the study area; (iii) use a material for the end caps which prevent biofilm formation.

Fig. 6. OPIC equipment assembling and testing: (A) lateral and (B) top view; (C) deployment in natural settings at St. Ives boatyard (UK) (2-column image).

3.3. *Future application, sample processing and analyses*

OPIC constitutes a new methodology to study plastic behaviour and fate in the marine environment and its proof of concept sets the baseline for future applications on moored array platforms to allow multi-years studies of a wide range of pre-selected virgin and/or aged plastic pieces and textiles.

OPIC has similar design and mechanics to sediment traps, as it is equipped with the same kind of stepping motor and rotation carousel, which has already been proven as suitable equipment for long-term monitoring studies in the open ocean and in the deep sea. Its features facilitate its installation alongside mooring line platforms for the deployment in the open ocean and at various depths. As proposed in Fig. 7, we suggest that the potential customised moored system with OPIC could be equipped with multiple sensors to measure seawater physical and chemical parameters and an automated rotating carousel to expose plastic samples to natural environmental conditions for defined time periods, up to 3 years.

Potential general challenges associated with OPIC operation at sea can be identified with those normally related to working with mooring platforms in the open ocean. Based on our experience, risks normally include difficulties during deployment (e.g. due to sea state, equipment deterioration, personnel experience) and/or recovery (e.g. failed mooring release mechanism, iceberg towing). Other uncommon issues potentially causing malfunction of the motor in this equipment can include software or battery failure. In sediment traps, failure of the rotation mechanism has rarely been observed also due to physical blockage of the equipment e.g. caused by a large marine organism entering the sediment trap funnel and altering/blocking the collection of samples. Considering these technical and practical challenges, caution should be used when operating with OPIC at sea, as normally done with other oceanographic instruments, to ensure OPIC function.

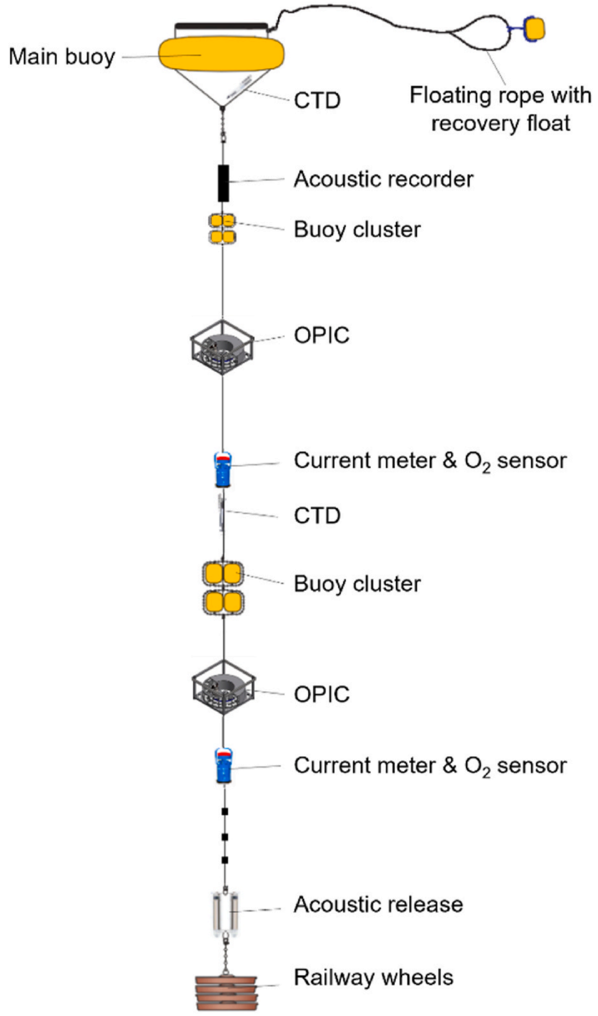

Fig. 7. Schematic of a potential mooring array with OPIC system deployed at different depths (1.5-column image).

In future application at sea, following OPIC recovery, plastic samples can be collected and replicates split for various analyses, as listed in Table 2. Plastic macroscopic features, such as weight loss and changes in size, colour and opacity can be determined following visual observation and weigh of the specimens. Changes in plastic mechanical properties as polymer density, tensile strength and crystallinity can be determined through sinking experiments, tensile testing and differential scanning calorimetry, respectively. Surface alteration and erosion over time is assessed through SEM, while changes in polymers chemical bond structures are detected using Fourier-transform infrared (FTIR) spectroscopy. The hydroxyl, carbonyl, carbon-oxygen indexes resulting from this analysis have been used as indicators of plastic surface oxidation and thus of plastic aging in natural settings (Brandon et al., 2016; ter Halle et al., 2017).

Furthermore, plastics incubated in OPIC can be analysed to evaluate the adsorption of contaminants from the surrounding seawater (Chen et al., 2018; Rochman et al., 2014; Syberg et al., 2020) as well as to determine the taxonomic resolution and temporal dynamics of the plastisphere, the presence of invasive species and antibiotic resistance (Ibabe et al., 2020; Laganà et al., 2019; Yang et al., 2019).

OPIC will be first employed within the project CUPIDO (CalcUlating the strength of the Plastic pump In counteracting the Deep export of Oceanic carbon, https://www.bas.ac.uk/project/cupido/) to monitor and parametrise plastic degradation naturally occurring in the mesopelagic zone of both temperate and polar regions. The application of OPIC as a long-term field platform to collect data also in the most remote and inaccessible regions (e.g., the deep sea and the poles) will provide a unique advantage to standardise the *in situ* monitoring of plastic degradation in different oceanic systems on a global scale.

4. Conclusions

UN 2030 Agenda and Ocean Decade initiatives have defined an ambitious Zero-pollution plan, in which plastic debris is recognised as one of the main stressors affecting the Ocean health and wealth worldwide. However, the lack of technologies to study plastic degradation at sea is a major limitation to determine the fate of marine plastic debris for risk assessment purposes.

OPIC is presented as a novel incubator equipment inspired by sediment trap design to monitor the time-series plastic degradation in the

Table 2
List of the features of plastic samples, (non-)destructive analyses and related outcomes indicative of long-term *in situ* plastic degradation, which can be determined using OPIC equipment.

Plastic feature(s)	Analysis	Marker of plastic degradation
Macroscopic	Visual observation, Weigh	Change in colour and size, weight loss
Mechanical	Sinking, Tensile testing, Differential scanning calorimetry	Change in buoyancy in seawater, tensile strength, crystallinity
Surface roughness	SEM	Embrittlement, Erosion
Chemical composition	FTIR	Hydroxyl, carbonyl, carbon-oxygen indexes
Biological colonization [a]	eDNA extraction and sequencing, Microbial characterization	Plastisphere composition, spread of invasive species, antibiotic resistance
Interaction with contaminants [a]	Chromatography	Chemicals adsorbed

[a] Plastic features acquired after incubation only.

open ocean, whose environment is difficult to reproduce under laboratory settings. OPIC was conceived to follow *in situ* how plastics of various polymers, size, shape and age degrade in the marine environment with a high temporal (multi-years) resolution.

To show proof of concept, in this study OPIC prototype was manufactured, assembled and improved following tests in house at BAS and in natural settings, to ensure its functionality at sea. Further engineering developments are also discussed, and potential future applications and samples analyses are presented as an example of the potential of this equipment.

Overall, the design of OPIC suggests that this equipment is ideal for long-term field experiments with incubation chambers "suspended" in the open ocean, fostering plastic pollution research towards a new holistic approach.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119868.

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