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Biodegradable twine for trawl fishing: Seawater ageing and net modelling

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ABSTRACT

Fishing gears are designed to catch marine species, but when lost at sea, they can continue to trap and kill aquatic life, a phenomenon known as ghost fishing. This study evaluated the use of a biodegradable twine made from poly(butylene succinate)/poly(butylene adipate terephthalate) (PBS/PBAT) in trawl fishing. The assessment included mechanical testing, trawl modelling, and seawater ageing simulations to explore potential loss scenarios. Mechanical tests indicated that the PBS/PBAT braid was about half as strong as high-density polyethylene (HDPE) but was suitable for braiding and netting. After 3 years in seawater, PBS/PBAT monofilaments showed biotic degradation, with strength losses of 20 % at 15 °C and 80 % at 25 °C. This suggests that gear made from this polymer would degrade faster than conventional gear if lost. Trawl modelling further demonstrated that trawl performance was only slightly affected by material change and ageing, highlighting the potential for reducing ghost fishing with less persistent twine.

1. Introduction

Fishing involves capturing aquatic species actively or passively and accounts for the largest share of aquatic resource production (FAO, 2024). Historically fishing gears were made of natural fibres such as cotton or hemp, but were replaced in the 1960s by more resistant, less visible, and more durable synthetic fibres like polyamide (PA) or high-density polyethylene (HDPE) (Matsushita et al., 2008; Hubert et al., 2012). During fishing operations, the gear may get caught on obstacles or entangled with other gear, resulting in its loss at sea (Richardson et al., 2018, 2021). Gear loss is considered the primary cause of plastic pollution in the life cycle of seafood products (Loubet et al., 2022), with fishing gear debris responsible for a large portion of the plastic waste in the open seas (Lebreton et al., 2022; Morales-Caselles et al., 2021). Fishing gears are engineered to capture species; this capture can continue even after being lost, referred to as ghost fishing. Ghost fishing affects all marine life, including birds (Ryan, 2018; Žydelis et al., 2006), mammals (Hanni and Pyle, 2000; Ramp et al., 2020; Stelfox et al., 2016), corals (Valderrama Ballesteros et al., 2018; Beneli et al., 2020), and fish (Beneli et al., 2020). In addition to inflicting harm and death on endangered species and juveniles (Hanni and Pyle, 2000; Ramp et al., 2020), lost fishing gear also poses risks to vessels and ships (Hong et al., 2017). Despite the seawater stability of polymers such as HDPE used for gear making (Le Gué et al., 2023), the mortality of ghost nets decreases over time due to the reduction of fishing surface and greater visibility because of bio-fouling (Humborstad et al., 2003). However, active fishing gear like seine and trawl nets are also prone to lose fragments (Richardson et al., 2019). Depending on their size, these fragments may contribute to ghost fishing; however, once they no longer ghost fish, they still add to plastic pollution by breaking down into small particles of plastics (Sharma et al., 2024) and accumulating in marine ecosystems due to the chemical stability of conventional polymers (Andrady, 2017). Besides causing physical damage to aquatic life (Wright et al., 2013), fishing gears made of conventional polymers are known to be a source of hazardous chemical additives (Jang et al., 2024).

There are ongoing efforts to create biodegradable polymers that are less harmful to the marine ecosystem (Wang et al., 2021). When exposed to seawater, these polymers break down more quickly than traditional ones, which could help reduce ghost fishing by decreasing their ability to catch marine life. However, they must be fully mineralised to avoid microplastic accumulation. While it may not always be necessary to use these polymers, such as in structures that can be retrieved at the end of their lifespan, their application is justified for fishing gear that is prone to loss and challenging to recover (Paul-Pont et al., 2023). Various biodegradable polyesters are currently available, differing in their sources and production methods. For instance, polyhydroxyalkanoates

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(PHAs) are naturally produced by microorganisms under specific conditions (Derippe et al., 2024; Palmeiro-Sánchez et al., 2022; Dilkes-Hoffman et al., 2019). In contrast, some polyesters, such as polycaprolactone (PCL), are entirely synthesized from petroleum-based derivatives (Suzuki and Tachibana, 2021; Yoshida et al., 2024; Sekiguchi et al., 2011; Ebisui et al., 2006). Others, like polybutylene-based polymers, combine bio-based and petroleum-derived components (Deroiné et al., 2019; Park and Bae, 2023; Le Gué et al., 2023; Grimaldo et al., 2023; Brakstad et al., 2022). The latter group has been widely studied in the literature for fishing gear such as ropes (Føre et al., 2023; Le Gué et al., 2023) and static gear such as gillnets (Grimaldo et al., 2019; Brakstad et al., 2022; Le Gué et al., 2024b), lines (Cerbule et al., 2022b) or pots (Cha et al., 2011; Kim and Lee, 2014). While some authors found that replacing conventional gear with biodegradable ones did not affect the catch efficiency of the gear (Bae et al., 2010; Cerbule et al., 2022a, 2023; Cerbule et al., 2022c; Kim and Lee, 2014; Kim et al., 2016, 2018; Yu et al., 2023), others found that it negatively affected the catch (Bae et al., 2012; Cerbule et al., 2022b; Grimaldo et al., 2019; Grimaldo et al., 2018a; Grimaldo et al., 2020a; Grimaldo et al., 2018b; Grimaldo et al., 2020b; Seonghun et al., 2014). The majority of published research highlights the fishing efficiency of static gears and the changes in their properties during fishing activities (Grimaldo et al., 2019, 2020a; Yu et al., 2023; Savina et al., 2024), but only a limited number of studies have investigated the degradation process of biodegradable gear in natural seawater (Kim et al., 2016; Brakstad et al., 2022; Kim et al., 2023, 2024; Le Gué et al., 2023, 2024b).

A previous study examined the suitability of a PBS/PBAT monofilament for rope-making, focusing on its durability after 18 months of exposure in natural seawater tanks (Le Gué et al., 2023). The findings revealed that, despite having a load at break half that of a commercial HDPE monofilament, the material remained interesting for rope-making applications. Furthermore, the PBS/PBAT monofilament underwent biotic degradation in conjunction with hydrolysis, leading to a gradual reduction in load at break over time. These characteristics suggest its potential as an effective material to mitigate ghost fishing in marine environments.

However, results on monofilament are not representative of the behaviour of the material in a fishing net configuration. Recent studies on PBSAT gillnets, including field tests at sea, revealed significant catch loss due to the inadequate strength of PBSAT nets (Savina et al., 2024). While the monofilament itself exhibited a load at break that was half that of polyamide 6 (PA6), this difference was amplified in knot configurations because of PBSAT's sensitivity to the stress concentrations they create (Le Gué et al., 2024a). At the knot scale, the load at break of PBSAT was only 25 % of that of PA6, highlighting the critical influence of knot performance on overall net behaviour. Furthermore, knots also accelerated degradation during exposure to biotic conditions, further weakening the net over time (Le Gué et al., 2024b). These findings underlined the need to evaluate both the structural complexity and durability of fishing gear under natural seawater conditions. These studies also highlight the necessity to investigate the impact of introducing a monofilament across the various scales specific to each type of fishing gear, both in its initial state and throughout the ageing process.

Existing research has focused predominantly on ropes or static gear, with no studies addressing active gear such as trawl nets, which are the most widely used systems (Rousseau et al., 2024) and are more prone to loss (Richardson et al., 2019). Several explanations can clarify the absence of studies on trawling gear. First, they are made up of braids of various diameters that require different braiding steps. These braids are then formed into net sheets with varying mesh sizes using bowline knots. The panels must then be assembled according to the selected trawl plan. Active gear nets, especially bottom trawls, are exposed to more rigorous conditions than passive gear. The complexity of these structures and the need for more material also make prototype manufacturing more expensive than passive gear. The high cost of prototypes and the challenging conditions could explain why no tests have been conducted yet. However, research in fishing technologies has developed methods to facilitate the design and prototyping of new trawls, mainly through the use of models in flume tanks (Winger et al., 2006; Druault and Germain, 2016; Thierry et al., 2020) and commercial simulation tools (Nguyen and Winger, 2016; Vincent, 2000). Trawl simulation software provides essential data about how gear design and properties affect fishing operation. The important parameters include towing tension, which is related to fuel consumption; net geometry, which affects the fishing efficiency of the gear; and the force exerted on the sediment for bottom trawls, which impacts the environment. These insights can be obtained without the need for costly sea trials (Queirolo et al., 2009). Some of these simulation tools, such as DynamiT, are based on material properties such as the stiffness, the density, and the construction of the twines (Nguyen and Winger, 2016; Vincent and Roullot, 2006), and can thus be used to investigate the impact of introducing an alternative material, such as a biodegradable monofilament, on trawl fishing operations.

The present study compares the performance of a PBS/PBAT twine to conventional commercial twines, focusing on the mechanical behaviour of knots and the long-term effects of seawater exposure. Although biodegradable monofilaments have been studied previously, this research is the first to investigate their application as twines and knots specifically designed for trawl fishing. The initial mechanical properties of both biodegradable and commercial materials were first assessed to estimate net resistance, with particular attention to knot properties, which are critical for evaluating the performance of biodegradable fishing gear. Twine ageing experiments were then performed to gain a deeper understanding of how the mechanical properties of the biodegradable monofilament and twine change during use in natural seawater conditions. A novel aspect of this research is the integration of trawl modelling to evaluate the behaviour of a trawl constructed from biodegradable twine. This approach allowed for a comparison of the initial mechanical properties of the biodegradable trawl with those of a conventional twine trawl. Furthermore, the modelling incorporated long-term ageing data to provide insights into the performance of the biodegradable trawl over time, offering a unique perspective on its potential as a sustainable alternative in fishing operations.

2. Materials and methods

2.1. Materials

Two monofilaments were examined: one made of PBS/PBAT as a safer alternative and one made of HDPE as the commercial reference. The PBS/PBAT monofilament, produced through extrusion and drawing, had a 0.35 mm diameter and was white. Its initial weight-average molecular weight was 25.6 kg/mol, exhibiting a polydispersity index of 4.8. In contrast, the reference HDPE monofilament was thinner, with a diameter of 0.28 mm, and was green. Both monofilaments were provided by Le Drezen and were identical to those used in an earlier study (Le Gué et al., 2023). Table 1 details their properties.

Twine samples made from these monofilaments were also tested and are presented in Fig. 1: one 5.5 mm PBS/PBAT twine, and 5.5 mm and 4 mm commercial HDPE twines. The PBS/PBAT twine consists of a

Table 1
Properties of the PBS/PBAT and HDPE monofilaments (Le Gué et al., 2023).

Property	PBS/PBAT	HDPE
Density [$g.cm^{-3}$]	1.285	0.956
Diameter [mm]	0.35	0.28
Tex [$g.km^{-1}$]	121.7	54.6
Young's Modulus [GPa]	0.79	1.90
Load at break [N]	25.1	21.4
Stress at break [MPa]	261	368
Strain at break [%]	34.5	40.5

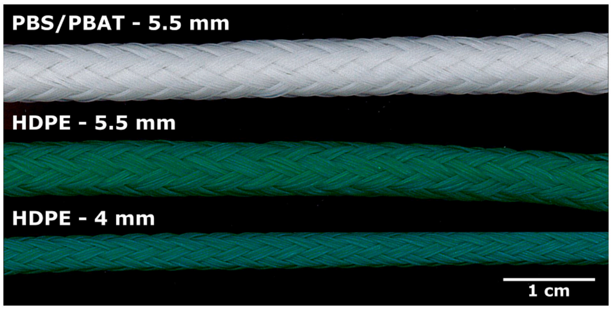

Fig. 1. PBS/PBAT and HDPE ropes used in the study.

braided cover made of 5*16 monofilaments arranged with a 35 mm pitch, and a core made of 20*3 monofilaments. The resulting linear mass is 17.0×10^3 g.km^{-1}. For the 5.5 mm and 4 mm HDPE twines, the linear masses are respectively 11.8×10^3 g.km^{-1} and 5.1×10^3 g.km^{-1}. To evaluate the knot strength of both PBS/PBAT and HDPE, simple weaver's knots were made from the 5.5 mm twines. The knots were made by hand using two 200 mm twine lengths.

2.2. Density measurement

A gas pycnometer was used to determine the density of HDPE and PBS/PBAT monofilaments by gas displacement (Richards and Bouazza, 2007). Before being placed in the pycnometer chamber, the samples were stored for 12 h in a room maintained at 21 °C and 50 % relative humidity; then their mass was measured using a balance with a precision of 0.1 mg. The analysis involved 10 cycles of purging to eliminate the air in the chamber, followed by the measurement of density based on the average value obtained from 20 analysis cycles. The pressure rate level required for equilibrium in each cycle was 0.015 psig/min.

2.3. Mechanical testing

Mechanical testing was performed on a 10 kN capacity tensile test machine in a room maintained at 21 °C with a relative humidity of 50 %. A 50 N load cell equipped with pneumatic grips specifically designed for testing fibres was used for monofilament testing. Testing fixtures for monofilament, twine, and knot samples were selected in accordance with ISO-1805 to ensure standardised testing conditions. The loads recorded during testing were normalised by the linear density (tex) of the samples, as specified in ISO-858. Monofilament samples were 50 cm in length, resulting in a gauge length of 30 cm. Twines and knots were tested using the same machine, equipped with a 10 kN load cell. Twine samples, each 150 cm long, were mounted in the machine by winding them three times around two 50 mm diameter pins. The resulting gauge length for twine samples was approximately 50 cm. The strain for monofilament and twine samples was measured using a Basler ac2440 digital camera, which tracked the distance between two markers placed on the samples. Digital camera measurements enabled displacement precision of 0.1 mm for monofilament and knot samples, and 0.5 mm for twine samples. The stiffness for both types of samples was calculated by determining the slope between 0 % and 5 % strain. Knot samples were tested by clamping their four ends in pneumatic grips in both normal and transverse directions. Markers were placed on the four ends of the knot and tracked with a digital camera to compute the tightening of the knot. Knot tightening was calculated using virtual points defined as the mean position of the two markers on the same horizontal side of the knot. The tightening of the knot was defined as the relative increase in the distance between these two virtual points during the test. For twine and knot samples, five replicates were tested at the initial state to ensure reliable measurements. In contrast to the ISO-1805 protocol, which specifies equivalent test durations based on sample type, a fixed displacement rate of 50 mm.min^{-1} was used for all tests. This approach ensured a consistent basis for effectively comparing the mechanical behaviour of PBS/PBAT and HDPE samples.

2.4. Seawater ageing

The samples were immersed in renewed natural seawater pumped from the Brest estuary on the western French coast, maintained at several temperatures. Sediment was removed from the seawater through sedimentation, and the volume of the 150 L tanks was renewed daily to ensure optimal water quality. Monofilament and twine samples were placed in plastic pots with holes to ensure water circulation. Monofilament samples were immersed in seawater tanks maintained at 4 °C, 15 °C, 25 °C, and 40 °C for three years. The 5.5 mm PBS/PBAT twine and the 4 mm HDPE twine were immersed at 25 °C and 40 °C for eight months. The water treatment was consistent throughout the entire duration of the experiments, ensuring uniform conditions for all samples. For twine inspection after seawater ageing at 25 °C, five monofilaments from both the inner core and the outer part of the twine were tested. Before any analysis, samples were dried for at least 12 h in the same environment-controlled room used for mechanical testing (21 °C, 50 % RH). Mechanical testing of aged samples was performed according to the methods described in the mechanical testing section, with three replicates conducted for each condition. The mechanical properties of aged samples are expressed relative to their initial values, providing a straightforward way to observe the effects of ageing on the materials.

2.5. Surface characterisation

Surface observations of pristine and aged samples were obtained through Scanning Electron Microscopy (SEM) using FEI Quanta 200 equipment. Before observation analysis, the samples were coated with 60 % gold and 40 % palladium to avoid surface charging.

2.6. Mechanical modelling

DynamiT software was employed for trawl simulations, enabling the modelling of a trawl and its rigging by solving structural and hydrodynamic equations based on a specified trawl design and numerical mesh (Vincent and Roullot, 2006). In this software, twines are represented as rigid, elastic bars connected by perfect knee joints, which exhibit no friction or elasticity (Vincent, 2000). The model accounts for the suppleness of the twines by subdividing the bars that represent them. However, the joints between the subdivided bars are modelled as perfect knee joints, meaning that no bending stiffness is considered in the simulation. To manage the complexity of a full trawl design, DynamiT utilises a globalisation parameter, which consolidates numerous individual meshes into larger equivalent virtual meshes. This approach significantly reduces computational demand while maintaining the mechanical and hydrodynamic equivalence of the actual net. Additionally, the software uses a maximum residue for equilibrium as its convergence criterion, controlling the deviation from equilibrium during the iterative process. The solution is considered converged when the residual error falls below the specified threshold, balancing accuracy and computational time.

Fig. 2 presents the trawl design used for simulations to compare the different materials, and Table 3 specifies the different net panels. The software requires the buoyancy coefficient b for each material, which is calculated from the density ρ as follows:

$$b = 1 - \rho \tag{1}$$

If the buoyancy coefficient is negative, the twine floats; if it is positive, it sinks. The buoyancy coefficients for PBS/PBAT and HDPE are 0.285 and $-$ 0.044, respectively. The stiffness of different twines and materials is used to assess mechanical behaviour. Since 4 mm PBS/PBAT twine and aged PBS/PBAT twine have not been tested, the values have been computed using a coefficient that considers the reduction in

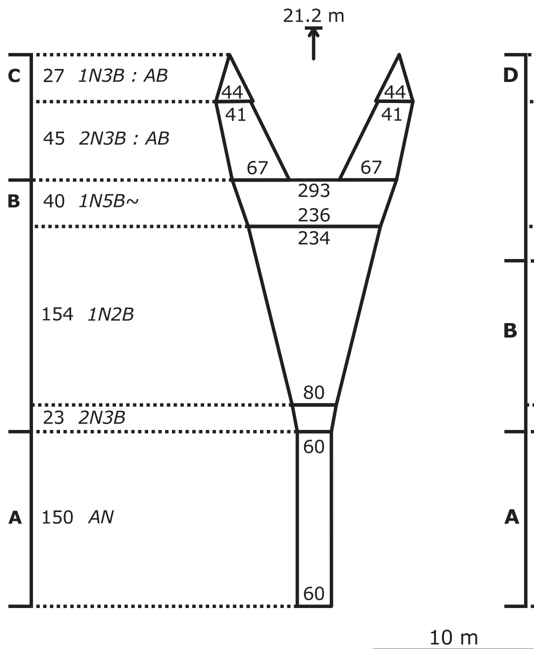

Fig. 2. Top (left) and bottom (right) panels composing the trawl used for simulations. Italic codes such as 1N2B represent the cutting rates, while integers denote the number of meshes. These values are used in trawl design to determine the dimensions of the various net panels.

stiffness between K_{mono}, the stiffness of the monofilament, and K_{mono}, the stiffness of the twine scale, both expressed in N.tex^{-1}.

$$a_{twine} = \frac{K_{twine}}{K_{mono}} \quad (2)$$

The stiffness of both pristine and aged 4 mm PBS/PBAT twines was estimated using the coefficient from the HDPE 4 mm twine, whereas the stiffness of the aged 5.5 mm PBS/PBAT twine was assessed using the coefficient from the PBS/PBAT 5.5 twine. The coefficients were 0.51 and 0.48, respectively. Table 2 presents the different stiffness values used for each model. As the software requires stiffness parameters to be expressed in Newtons, these values are presented accordingly.

Simulations were conducted at a fixed depth of 100 m with various trawling speeds: 2.0, 2.5, 3.0, 3.5, and 4.0 knots. The numeric mesh sides chosen for globalisation were 0.9 m and 1 m for the top and bottom panels, respectively. The mesh created had 1932 bars, exceeding the recommended minimum of 1000 bars for good net representativity. For all simulations, a time step of 1×10^{-4} s and a residue of 1×10^{-8} were used to ensure good convergence for comparing the different materials. The following parameters were then retrieved for comparison: otter boards opening, which determine the lateral spread of the trawl; horizontal and vertical openings, which refer to the dimensions of the trawl mouth in both the horizontal and vertical planes; swept water volume, which measures the volume of water displaced by the trawl during operation; total weight on the seabed, which quantifies the weight applied by the trawl on the seabed; and towing traction, which represents the force required to tow the trawl through the water.

Table 2
Stiffness [N] values for various twines used in each model (HDPE, PBS/PBAT, aged PBS/PBAT). Values denoted by an asterisk were calculated using (2). Values in italic were retrieved from (Le Gué et al., 2023).

	HDPE	PBS/PBAT	PBS/PBAT aged
monofilament	*153*	*100*	69
4 mm twine	7314	4285*	2939*
5.5 mm twine	14,615	6479	4444*

Table 3
Mesh size and twine diameter for the different net panels composing the trawl.

Panel	Mesh size [mm]	Diameter [mm]
A	40	5.5
B	40	4
C	60	4
D	60	5.5

Table 4
Knot strength [kN] for PBS/PBAT and HDPE in both transverse and normal direction.

	PBS/PBAT	HDPE
Normal	3.8 ± 0.1	4.9 ± 0.3
Transverse	3.9 ± 0.1	4.8 ± 0.4

Table 5
Model output for a trawling speed of 3.0 kn and a depth of 100 m.

Model output	HDPE	PBS/PBAT	PBS/PBAT aged
Otter boards opening [m]	51.3	51.3	51.5
Horizontal opening [m]	11.0	11.0	11.1
Vertical opening [m]	2.6	2.4	2.4
Swept water volume [$m^3.s^{-1}$]	56.8	53.4	53.9
Total weight on the seabed [kN]	3.9	4.2	4.2
Towing traction [kN]	26.6	26.6	26.5

3. Results and discussion

3.1. Mechanical testing

Fig. 3 presents the tensile curves of PBS/PBAT and HDPE at both the monofilament and twine scales. Monofilament curves were retrieved from a previous study (Le Gué et al., 2023). Each curve corresponds to a tested specimen, with the load normalised by its tex, facilitating a comparison of the behaviour between the monofilament scale and the twine scale and between the two materials. There was a marked

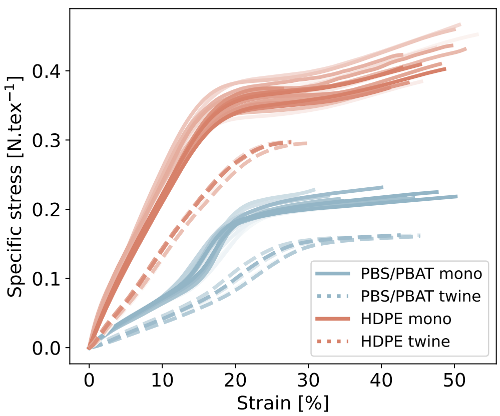

Fig. 3. Tensile test curves of PBS/PBAT and HDPE at different scales (monofilament, twine). Monofilament data were obtained from (Le Gué et al., 2023).

decrease in stiffness for both PBS/PBAT and HDPE materials when scaled from monofilament to twine, with reductions of 52 % and 55 %, respectively. This significant drop in stiffness is mainly due to how the twines are structured. The core of the braid is twisted at a specific angle, and the outer cover is woven. When the braid is subjected to stress, the strand orientation changes, causing the braid to deform more easily, which leads to lower stiffness. However, the difference in stiffness of the PBS/PBAT twine is still important, being 68 % lower than the stiffness of the HDPE twine. Specific load at break is 47 % lower for the PBS/PBAT monofilament compared to HDPE, but at the twine scale, both PBS/PBAT and HDPE undergo equivalent loss of respectively 24 % and 27 %. Given that the loss in specific strength is comparable, the disparity between PBS/PBAT and HDPE matches that of the monofilament, with the specific strength of the PBS/PBAT twine being 45 % lower. Additionally, the strain at break for HDPE twine is reduced compared to its monofilament. For PBS/PBAT, the strain at break of the twine is equivalent to that of the monofilament. As a result, it can withstand higher strain before failure. The PBS/PBAT twine appeared weaker than the HDPE reference, but testing the twine is not sufficient to estimate or compare the strength of the materials in a net configuration (Le Gué et al., 2024a). Weaver's knot testing was then conducted to compare both materials further and better approach the strength of a net made from these twines.

Fig. 4 summarises the results obtained from knot testing both materials in normal (0°) and transverse (90°) directions. To determine the specific strength of the knot, the strength values were adjusted based on the twine's tex and then divided by two, as each knot is made up of two twines. Table 4 provides the strength values obtained in kN. The weaver's knot properties for PBS/PBAT and HDPE were comparable in both normal and transverse orientations, suggesting that the resistance of twine-made weaver's knots remains unchanged regardless of the loading direction. The presence of the knot still impacted the strength compared to twines without a knot: the PBS/PBAT knot induced a 29 % reduction. A very similar reduction was measured for HDPE, showing a 30 % lower strength. At equivalent tex, the strength of the PBS/PBAT knot would, therefore, be half that of the HDPE knot, resulting in a weaker net. However, if the use of a thicker monofilament is possible, PBS/PBAT could already be used as a substitute material.

In addition, the PBS/PBAT knot required less load to tighten, leading to higher tightening at break and a less stiff knot. This might affect the selectivity of the gear by altering the mesh shape and openness (Bak-Jensen et al., 2023), which could also affect the drag of the entire gear (O'Neill and Breddermann, 2024). The knots could also tighten more easily during towing, potentially altering the mesh size and further influencing selectivity.

Fig. 5 illustrates the comparative difference in performance between PBS/PBAT and HDPE for various tested scales. The performance disparity between PBS/PBAT and HDPE remains uniform across these scales, indicating that braiding and knotting do not impact the effectiveness of the biodegradable polymer, unlike the findings from previous tests on a biodegradable gillnet (Le Gué et al., 2024a). The PBS/PBAT is thus suitable for trawl netting, with particular attention focused on the knot stabilisation process as it involves heat and humidity, which could degrade the polymer chains.

PBS/PBAT is indeed more sensitive to water than HDPE and undergoes biotic degradation in the presence of microorganisms (Kim et al., 2016, 2023; Le Gué et al., 2023), the properties of the twines may then change with immersion time. As reported in a previous study, biotic degradation is influenced by the structure, which depends on the choice of biodegradable material (Le Gué et al., 2024b). Therefore, ageing tests were conducted to more accurately evaluate the changes in the twine's properties when immersed in seawater, to determine its performance during service, and to understand its degradation behaviour if lost.

3.2. Durability in the marine ecosystem

Fig. 6 illustrates the variations in tensile behaviour observed after 8 months of immersion for both the PBS/PBAT twine and the HDPE

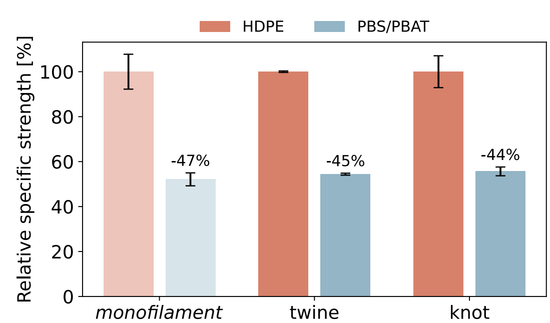

Fig. 5. Comparison of the relative specific strength of both HDPE and PBS/PBAT at monofilament, twine, and knot scale. Monofilament data were obtained from (Le Gué et al., 2023).

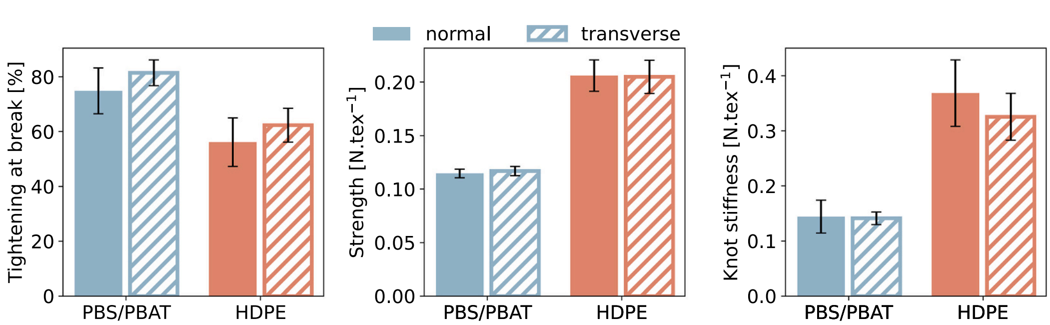

Fig. 4. Mechanical properties of PBS/PBAT and HDPE knots in normal and transverse directions.

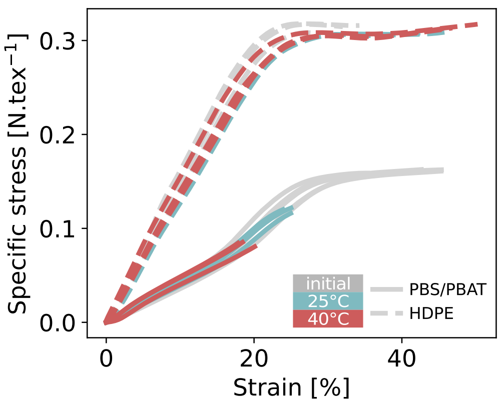

Fig. 6. Tensile test curves for PBS/PBAT and HDPE twines before and after eight months of immersion in 25 °C and 40 °C seawater.

reference twine. The HDPE twine did not lose any strength or stiffness after ageing, regardless of the temperature. For the PBSAT twine, a difference in tensile behaviour after ageing is observed. After being immersed for 8 months at 25 °C and 40 °C, the twine experienced a reduction in its original strength by 26 % and 46 %, respectively, while its stiffness remained unaffected. The mechanisms behind the degradation were previously documented: biotic degradation and hydrolysis occurred in samples at 25 °C, whereas hydrolysis was the primary factor reducing strength at 40 °C. While both mechanisms occur at 25 °C, biotic degradation is the more severe. Biotic degradation is known to occur at the surface of the polymer (Kim et al., 2016). Twines are composed of a braid of intertwined monofilaments that often surround a core made of slightly twisted monofilaments (see section 2.1 for more details). Biotic degradation might impact these monofilaments in various ways due to their arrangement, the resultant curvature, and specific location within the rope.

Surface observations of the braid and core of the PBS/PBAT twine after 8 months of ageing in 25 °C seawater are shown in Fig. 7. The outer part of the twine showed more significant signs of degradation compared to the inside, featuring more holes, resulting in a more consistent surface deterioration. The interior of the rope exhibited similar holes, but they were less frequent and more widely spaced. The stress induced by the bending of the monofilament speeds up biotic degradation. Nevertheless, the curvature of the braided monofilament is less pronounced than that within a knot. The lower degradation seen on the inner part of the rope is attributed to a protective effect from the outer layer, which shields it from further damage.

This non-uniform degradation could lead to a different degradation of mechanical properties when testing a monofilament alone. Differences in strength between initial and aged samples for monofilament, twine, and knot were then compared to assess the relevance of monofilament ageing when studying materials used for twine. Fig. 8 shows the relative difference in strength for different scales after 8 months of seawater ageing at 25 °C and 40 °C. After 8 months at 25 °C and 40 °C, the tensile strength of the monofilament decreased by 27 % and 47 %, respectively, from its initial value. Twines were mechanically tested after ageing at 25 °C to assess the effect of differential erosion between the inner and outer sections of the twine. The load at break tests yielded values of 16.2 ± 1.0 N for inner monofilaments and 14.3 ± 1.6 N for outer monofilaments. Although a slight variation was observed, it was not substantial enough to influence the overall ageing rates between the monofilament and twine scales. This difference was also noted at the knot scale used here to represent the net. This indicates that monofilament ageing can serve as a reliable predictor for the ageing behaviour of twine when exposed to seawater.

Monofilaments from the same batch of PBS/PBAT were immersed in seawater at natural temperatures for an extended period to evaluate the net's characteristics after three years in seawater. The investigation of degradation at 40 °C was excluded, as high temperatures impede biotic degradation by halting microbial activity (Zobell and Conn, 1940), leaving only hydrolysis to occur (Le Gué et al., 2024b). This renders the study of biotic degradation less relevant at such temperatures, as hydrolysis alone causes a complete loss of mechanical properties within a year, as demonstrated in previous studies (Le Gué et al., 2023). The mechanical properties of the monofilament were first examined to extrapolate and understand the net's performance in service or following a potential loss. Fig. 9 shows the relative change of the strain at break, load at break, and stiffness of the monofilament with immersion time at 4 °C, 15 °C, 25 °C and 40 °C. After 3 years at 4 °C, the monofilament showed inconsistent change of strain and load at break and no shift in stiffness, and therefore, no degradation of the mechanical properties was noted for the monofilament at this temperature. Samples aged at 15 °C exhibited no alterations until reaching 18 months, after which a slight reduction in both strain and load at break was observed. The reduction in mechanical properties was more significant for ageing at 25 °C, with

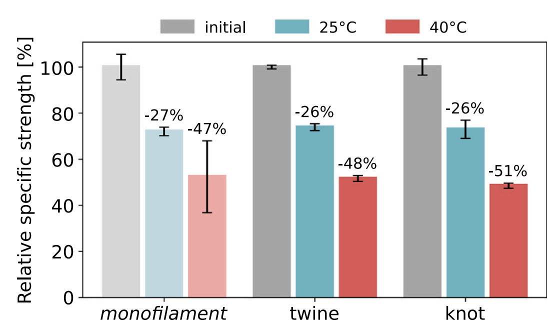

Fig. 8. Relative difference in PBS/PBAT strength for different scales after 8 months of seawater ageing at 25 °C and 40 °C.

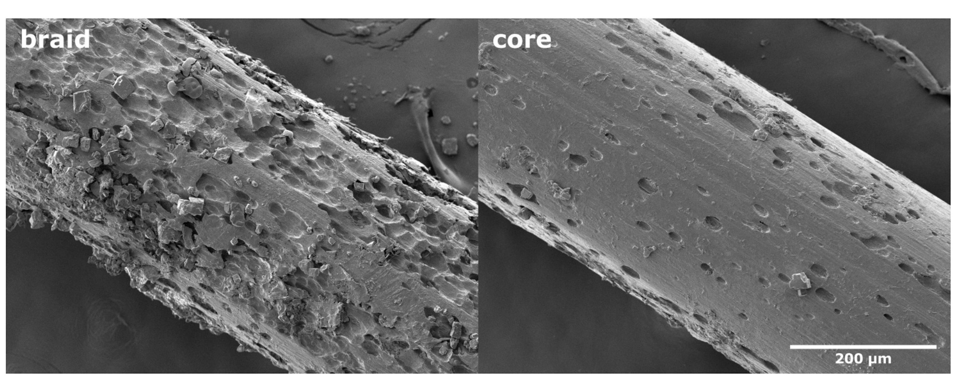

Fig. 7. Surface observations of monofilaments extracted from the braid and the core of the PBS/PBAT twine after 8 months of immersion at 25 °C.

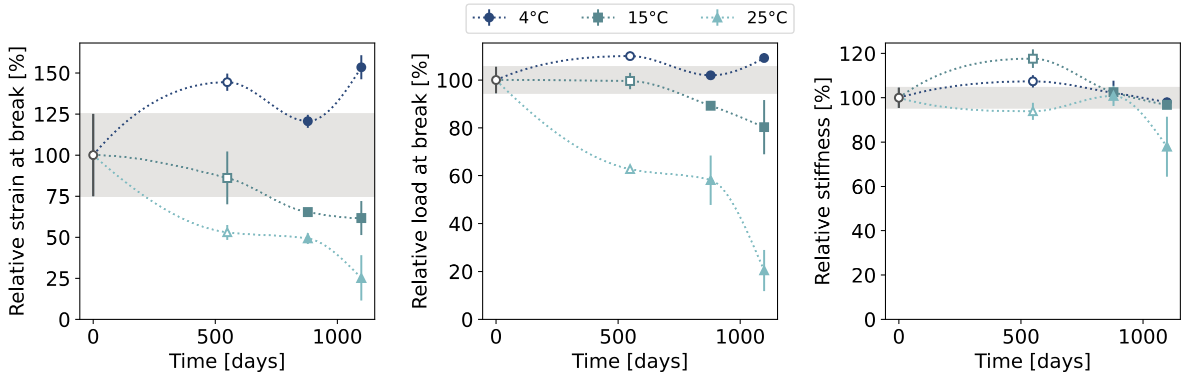

Fig. 9. Relative change in the strain at break, the load at break, and the stiffness with immersion time in seawater for the PBS/PBAT monofilament. Markers featuring a white interior were obtained from (Le Gué et al., 2023).

only 25 % of the initial strain and 20 % of the initial load at break remaining. A decline in the stiffness of the monofilament was also observed after 3 years of ageing. The results at 15 °C and 25 °C suggest that the gear would be likely to lose properties if lost at sea, but also during its service phase. A better understanding of the degradation mechanisms and kinetics is thus necessary.

The surface of the monofilament samples has been observed with SEM before and after 3 years of ageing and is shown in Fig. 10. No change in the surface morphology was observed after 3 years at 4 °C, which is coherent with the results obtained on mechanical properties. After being immersed at 15 °C for 3 years, small holes of several microns were noticed at various localised spots. The reduced properties observed at failure for this temperature might result from the holes serving as crack initiation points. The limited number of these holes also accounts for their minimal impact on the stiffness of the monofilament because this property is primarily determined by the material's atomic structure and chemical bonds (Callister, 2007). At 25 °C, surface degradation was more severe, resulting in holes that varied in size from a few microns to several tens of microns, consequently causing a significant decrease in load and strain at break according to mechanical testing. The decrease in stiffness observed at this temperature may be due to the reduction in cross-section caused by the extensive surface erosion rather than a change in the polymer structure. The erosion pattern at this temperature has already been observed on monofilaments made of PBS (Kim et al., 2023), PBSAT (Brakstad et al., 2022; Le Gué et al., 2024b), or PBS/PBAT (Kim et al., 2016; Le Gué et al., 2023) and is known to be caused by microorganisms. Differences in biotic degradation patterns between 15 °C and 25 °C have been documented in a previous study on PBSAT (Le Gué et al., 2024b): the degradation at 15 °C was characterised by deeper and more localised holes. In contrast, at 25 °C the degradation was more severe and evenly distributed on the surface. Similar observations were made in this study for longer immersion time on a PBS/PBAT blend, which underlines the importance of a better understanding of the nature and behaviour of the microorganisms present at both temperatures. Comparing the different studies reveals that the presence of surfaces unaffected by degradation is similar for pure PBS (Kim et al., 2023), PBSAT (Brakstad et al., 2022; Le Gué et al., 2024b), and PBS/PBAT (Kim et al., 2016; Le Gué et al., 2023). This suggests that these unaffected areas are independent of the type of polymer or environmental conditions. Further investigation is necessary to determine if they eventually degrade to prevent the production of microplastics from these biodegradable polymers, which could negatively impact the environment in a

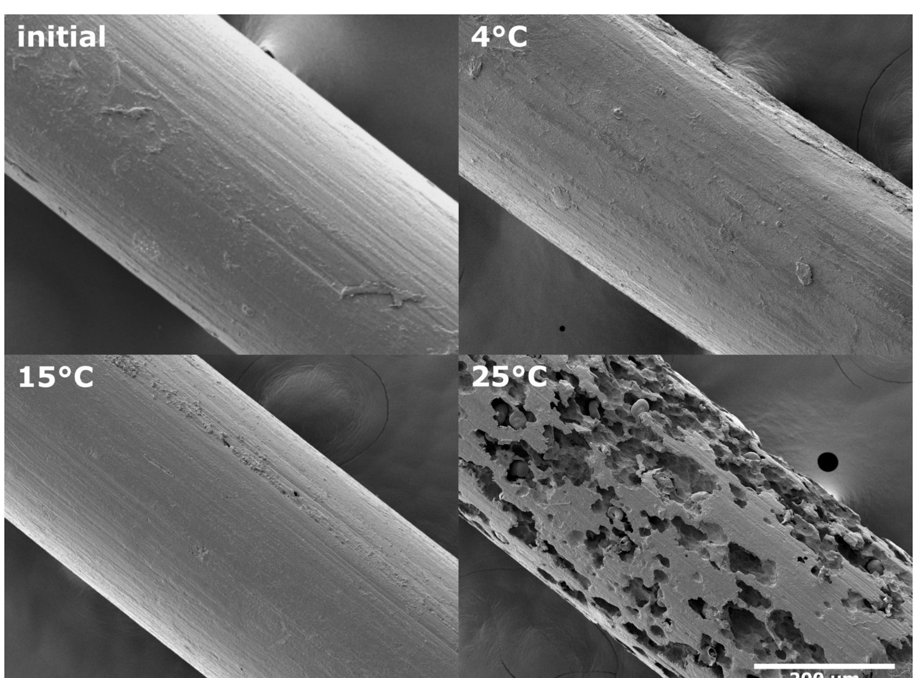

Fig. 10. Surface observations of PBS/PBAT monofilament samples before and after three years of seawater ageing at 4 °C, 15 °C, and 25 °C.

similar way to traditional plastics (Zimmermann et al., 2020; Malafeev et al., 2023; Limonta et al., 2024).

These long-term ageing results enable the estimation of the lifespan of the fishing net in use as well as the persistence of fragments that may be lost during fishing operations. The lack of property degradation during seawater exposure at 4 °C suggests that fishing gear composed of PBS/PBAT would remain intact in cold aquatic environments, implying that the gear would retain its stability over time but then pose the same issues as the conventional polymers it aims to replace. Moreover, because the density of PBS/PBAT exceeds that of seawater, any lost gear or fragment is likely to settle on the ocean floor (Bergmann et al., 2017), where temperatures approximate 4 °C or lower (Cutler et al., 2003), and could accumulate in the sediment if it is not mineralised (Van Cauwenberghe et al., 2013). Yet, the microorganisms found in the seawater tank are probably not representative of those at similar sea temperatures, as the ones from Brest's estuary are not acclimated to such cold conditions. To clarify these points, in-situ experimentation is crucial to understand better the fate of such polymers in cold aquatic environments. At 15 °C, the monofilament's biotic degradation was slow, resulting in a slight decrease in breaking properties after 3 years of immersion. At 25 °C, degradation occurred more rapidly, causing the monofilament to lose its mechanical strength after 3 years of immersion. The duration over which a trawl net remains functional can range from 3 to 5 years based on its application, although it is not submerged for such extended periods during its lifespan. In addition, allowing the net to dry between two campaigns can kill the biofilm, resulting in a different type of ageing compared to the continuous biotic ageing observed in the study. Also, in real-life conditions, the net is subject to other degradation factors, such as UV exposure and abrasion. To estimate the lifespan of a trawl net during use, it is necessary to further study this by conducting UV ageing and abrasion tests along seawater ageing. Once fishing gear is lost at sea, it is no longer subject to UV radiation or wear and tear from trawling activities, and the tests conducted here then give a realistic assessment of its behaviour in the marine environment. The reduction in mechanical properties observed at 15 °C and 25 °C was caused by microorganisms present in the marine environment. This suggests that if the net is lost, it will progressively lose its mechanical integrity with immersion time. As a result, its potential threat to ghost fishing would decrease. Thus, a PBS/PBAT net would present a safer alternative than the conventional HDPE nets. However, although marine microorganisms can degrade this polymer, this study does not evaluate its ultimate mineralisation or ecotoxicity, and further tests are therefore needed to better understand the impact of this polymer at sea. Furthermore, adopting biodegradable fishing gear requires the alternative material to be as effective as the conventional material (Drakeford et al., 2023). Based on mechanical tests in the initial state and ageing data, the trawling behaviour of a net made from PBS/PBAT, whether aged or not, was therefore compared with that of a conventional HDPE net.

3.3. Trawl modelling

The DynamiT model was used to calculate the characteristics of the trawl net for bottom trawling at a depth of 100 m, considering the diverse properties of each material and twine and accounting for varying towing speeds. Fig. 11a depicts vertical and horizontal opening variation with towing speed for HDPE, PBS/PBAT, and aged PBS/PBAT nets. The vertical opening for the HDPE is higher than that of the PBS/PBAT net until 3.5 knots, where the opening becomes similar. Ageing did not influence the vertical opening, with values for the aged PBS/PBAT net being the same as those for the pristine one. At low towing speeds, the horizontal opening is the same for HDPE and PBS/PBAT nets. As the speed increases, the horizontal opening for PBS/PBAT becomes higher, first for the aged net and then for the one in its initial state. Replacing HDPE twines with less stiff twines led to a greater horizontal opening of the trawl mouth, resulting in smaller vertical openings, except for higher trawling speed, where horizontal and vertical openings became greater than the ones from HDPE. However, the observed differences are relatively small compared to the trawl net dimensions. Fig. 11b presents representations of the different trawl mouths when trawling at 3.0 knots. The differences between the materials, including the various states of PBS/PBAT, were minimal at this stage. No variations were seen in the bottom panels, and the differences in the top panels were negligible despite the significant difference in twine stiffness.

Other outputs of the model have been compared to further study the difference between both materials at a fixed towing speed of 3.0 knots. Table 5 presents the values retrieved for the different outputs. It can be

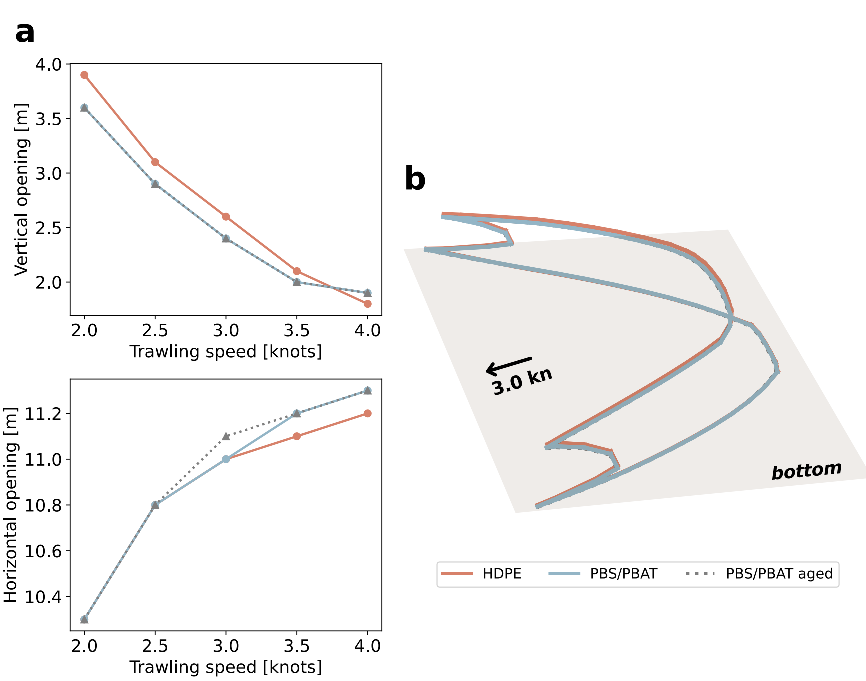

Fig. 11. a. Vertical and horizontal opening change with trawling speed b. Shapes of trawl mouths at 3.0 knots of trawling for the different materials and ageing (HDPE, PBS/PBAT, PBS/PBAT aged).

seen that despite having the same otter board opening and then the same horizontal opening at this speed, the vertical opening is lower for the PBS/PBAT net. The difference in vertical opening may be caused by the contrast in density between HDPE and PBS/PBAT. The latter is denser than water and sinks, while HDPE twines float. Because of this slight difference in vertical opening also observed in Fig. 11, the PBS/PBAT net swept 3 m^3 less per second than the reference net. For one hour of fishing, the PBS/PBAT net would have filtered 12,240 cubic meters less than the HDPE net. This could lead to lower catches or increased fuel consumption, as the vessel may need to travel at higher speeds to compensate for the reduced haul volume. Small changes can have a significant impact when considering the overall life cycle of a product. Conducting a life cycle analysis could help better estimate whether this overconsumption is significant in the context of the entire life of the PBS/PBAT gear. The weight of the PBS/PBAT net on the seabed was 8 % greater than that of the conventional net, which is relatively small compared to the 66 % higher mass of the PBS/PBAT net. Both the reduced vertical opening and the more important weight on the seabed could be compensated for by changing the buoyancy of the whole gear with additional floats. The towing traction, or the energy required to pull the trawl, was similar for both the PBS/PBAT and HDPE nets. The substitution of HDPE with PBS/PBAT will not impact the vessel's fuel consumption. The comparable drag results from the same diameter twines being used for both the PBS/PBAT and HDPE nets. Nevertheless, a PBS/PBAT net with identical diameters would exhibit reduced tensile strength relative to an HDPE net, which may cause higher gear loss rates. Braid strength is also the only parameter that varies with time in the trawl, as none of the output parameters of the model are affected by the decrease in stiffness observed as the monofilament aged at 25 °C. This highlights the need for more accurate assessments of the load on trawl nets during snagging or gear interactions to determine if increased thickness is genuinely required or if it leads to unnecessary oversizing. Further studies should also consider other factors, such as the abrasion resistance of braids and knots, as well as UV exposure, to ensure the durability of biodegradable monofilaments without relying on thicker twines that would increase fuel consumption. Although DynamiT does not account for knot rigidity and twine stiffness, these factors could significantly impact cod-end selectivity and mesh opening in scenarios involving catch modelling. Consequently, while the replacement of commercial braid with biodegradable braid is expected to have minimal effects on trawling operations, studying the impact of this material change on gear selectivity is essential, for example, via fish escape modelling (Vincent et al., 2022), and employing a trawl model that considers bending stiffness and mesh opening (Vincent et al., 2020).

4. Conclusion

Using less persistent fishing gear is necessary to reduce the harm caused by lost gear. To achieve this, it is essential to gain a deeper understanding of the use of alternative materials such as biodegradable polymers. This study examined the durability of a PBS/PBAT twine through mechanical testing and seawater ageing. Additionally, the study investigated the viability of utilising this twine to replace the current commercial HDPE twine by modelling a trawl based on the acquired experimental data. Mechanical testing at monofilament, twine, and knot scales revealed that the PBS/PBAT has half the strength of the HDPE. However, the consistency in the difference between both materials across the scales indicates that the PBS/PBAT is not sensitive to braiding or knotting and is thus suitable for net making. The observation of biotic degradation in seawater at 15 °C and 25 °C, with the loss of nearly all strength after three years at 25 °C, indicates that in the event of a loss, ghost gear made of PBS/PBAT would lose its properties at a much faster rate than one made from HDPE, and would therefore be less harmful to the environment. Using the DynamiT modelling software in conjunction with the acquired experimental data demonstrated that deploying a biodegradable twine would not influence trawl performance or configuration greatly, even when considering the effects of prolonged ageing. The results demonstrate that achieving the same trawl performances with less persistent twine is feasible, marking a significant step towards reducing the environmental impact of lost fishing gear. However, it is crucial to recognise that adopting less persistent gear is only one part of the solution to ghost fishing. Comprehensive measures must be implemented to prevent gear loss in the first place, ensuring a more sustainable approach to fishing.

CRediT authorship contribution statement

Louis Le Gué: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mael Arhant:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Peter Davies:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benoit Vincent:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Erwan Tanguy:** Writing – review & editing, Resources, Investigation, Conceptualization.

Declaration of competing interest

The authors received materials from Le Drezen and Erwan Tanguy is an employee of Le Drezen. However, these affiliations did not influence the design, interpretation, or reporting of the findings.

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Data availability

Data will be made available on request.

References

Andrady, A.L., 2017. The plastic in microplastics: a review. Mar. Pollut. Bull. 119, 12–22. https://www.sciencedirect.com/science/article/pii/S0025326X1730111X. https://doi.org/10.1016/j.marpolbul.2017.01.082.

Bae, B.S., An, H.C., Jeong, E.C., Park, H.H., Park, S.W., Park, C.D., 2010. Fishing power estimation of biodegradable traps in the East Sea. Journal of the Korean Society of Fisheries and Ocean Technology 46, 292–301. URL: http://koreascience.or.kr/article/JAKO201008863883138.page, doi: https://doi.org/10.3796/KSFT.2010.46.4.292. Publisher: the Korean Society of Fisheries and Ocean Technology.

Bae, B.S., Cho, S.K., Park, S.W., Kim, S.H., 2012. Catch characteristics of the biodegradable gill net for flounder. Journal of the Korean Society of Fisheries and Ocean Technology 48, 310–321. URL: http://koreascience.or.kr/article/JAKO201214350260540.page, doi: https://doi.org/10.3796/KSFT.2012.48.4.310. Publisher: the Korean Society of Fisheries and Ocean Technology.

Bak-Jensen, Z., Herrmann, B., Santos, J., Melli, V., Stepputtis, D., Feekings, J.P., 2023. The capability of square-meshes and fixed-shape meshes to control codend size selection. Fish. Res. 264, 106704. URL: https://linkinghub.elsevier.com/retrieve/pii/S0165783623000978 https://doi.org/10.1016/j.fishres.2023.106704.

Beneli, T., Pereira, P., Nunes, J., Barros, F., 2020. Ghost fishing impacts on hydrocorals and associated reef fish assemblages. Mar. Environ. Res. 161, 105129. URL: https://linkinghub.elsevier.com/retrieve/pii/S014111362030581X https://doi.org/10.1016/j.marenvres.2020.105129.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., Gerdts, G., 2017. High quantities of microplastic in Arctic Deep-Sea sediments from the HAUSGARTEN observatory. Environ. Sci. Technol. 51, 11000–11010.

https://pubs.acs.org/doi/10.1021/acs.est.7b03331. https://doi.org/10.1021/acs.est.7b03331.
Brakstad, O.G., Sørensen, L., Hakvåg, S., Føre, H.M., Su, B., Aas, M., Ribicic, D., Grimaldo, E., 2022. The fate of conventional and potentially degradable gillnets in a seawater-sediment system. Mar. Pollut. Bull. 180, 113759. URL: https://www.sciencedirect.com/science/article/pii/S0025326X22004416 https://doi.org/10.1016/j.marpolbul.2022.113759.
Callister, W.D., 2007. Materials Science and Engineering: An Introduction, 7th ed ed. John Wiley & Sons, New York (OCLC: ocm61463872).
Cerbule, K., Grimaldo, E., Herrmann, B., Larsen, R.B., Brčić, J., Vollstad, J., 2022a. Can biodegradable materials reduce plastic pollution without decreasing catch efficiency in longline fishery? Mar. Pollut. Bull. 178. https://doi.org/10.1016/j.marpolbul.2022.113577.
Cerbule, K., Herrmann, B., Grimaldo, E., Larsen, R.B., Savina, E., Vollstad, J., 2022b. Comparison of the efficiency and modes of capture of biodegradable versus nylon gillnets in the Northeast Atlantic cod (Gadus morhua) fishery. Mar. Pollut. Bull. 178. https://doi.org/10.1016/j.marpolbul.2022.113618.
Cerbule, K., Herrmann, B., Trumbić, Z., Petrić, M., Šifner, S.K., Grimaldo, E., Larsen, R.B., Brčić, J., 2023. Use of biodegradable materials to reduce marine plastic pollution in small scale coastal longline fisheries. J. Nat. Conserv. 74, 126438. URL: https://linkinghub.elsevier.com/retrieve/pii/S1617138123001097 https://doi.org/10.1016/j.jnc.2023.126438.
Cerbule, K., Savina, E., Herrmann, B., Larsen, R.B., Paul Feekings, J., Ahm Krag, L., Pellegrinelli, A., 2022c. Quantification of catch composition in fisheries: a methodology and its application to compare biodegradable and nylon gillnets. J. Nat. Conserv. 70, 126298. URL: https://linkinghub.elsevier.com/retrieve/pii/S1617138122001716 https://doi.org/10.1016/j.jnc.2022.126298.
Cha, B.J., Lee, G.H., Park, S.U., Cho, S.K., Lim, J.H., 2011. Development of the biodegradable octopus pot and its catch ability comparison with a polyethylene (PE) pot. Journal of the Korean Society of Fisheries and Ocean Technology 47, 10–17. URL: http://koreascience.or.kr/article/JAKO201108863885305.page, doi: https://doi.org/10.3796/KSFT.2011.47.1.010. Publisher: the Korean Society of Fisheries and Ocean Technology.
Cutler, K.B., Edwards, R.L., Taylor, F.W., Cheng, H., Adkins, J., Gallup, C.D., Cutler, P.M., Burr, G.S., Bloom, A.L., 2003. Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. Earth Planet. Sci. Lett. 206, 253–271. https://www.sciencedirect.com/science/article/pii/S0012821X0201107X. https://doi.org/10.1016/S0012-821X(02)01107-X.
Deripe, G., Philip, L., Lemechko, P., Eyheraguibel, B., Meistertzheim, A.L., Pujo-Pay, M., Conan, P., Barbe, V., Bruzaud, S., Ghiglione, J.F., 2024. Marine biodegradation of tailor-made polyhydroxyalkanoates (PHA) influenced by the chemical structure and associated bacterial communities. J. Hazard. Mater. 462, 132782. URL: https://linkinghub.elsevier.com/retrieve/pii/S0304389423020666 https://doi.org/10.1016/j.jhazmat.2023.132782.
Deroiné, M., Pillin, I., Le Maguer, G., Chauvel, M., Grohens, Y., 2019. Development of new generation fishing gear: a resistant and biodegradable monofilament. Polym. Test. 74, 163–169. URL: https://www.sciencedirect.com/science/article/pii/S0142941818311711 https://doi.org/10.1016/j.polymertesting.2018.11.039.
Dilkes-Hoffman, L.S., Lant, P.A., Laycock, B., Pratt, S., 2019. The rate of biodegradation of PHA bioplastics in the marine environment: a meta-study. Mar. Pollut. Bull. 142, 15–24. https://www.sciencedirect.com/science/article/pii/S0025326X19302048. https://doi.org/10.1016/j.marpolbul.2019.03.020.
Drakeford, B.M., Forse, A., Failler, P., 2023. The economic impacts of introducing biodegradable fishing gear as a ghost fishing mitigation in the English Channel static gear fishery. Mar. Pollut. Bull. 192, 114918. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X23003491 https://doi.org/10.1016/j.marpolbul.2023.114918.
Druault, P., Germain, G., 2016. Analysis of hydrodynamics of a moving trawl codend and its fluttering motions in flume tank. European Journal of Mechanics - B/Fluids 60, 219–229. URL: https://www.sciencedirect.com/science/article/pii/S0997754616302515 https://doi.org/10.1016/j.euromechflu.2016.06.010.
Ebisui, A., Murakami, H., Oyaizu, Y., Enoki, M., Kanehiro, H., Wakabayashi, S., Watanabe, T., 2006. Biodegradation of poly (ε-caprolactone) monofilament fibers in deep seawater at near 0°C. Deep Ocean Water Research 7, 31–35. https://doi.org/10.11174/dowas2000.7.2_31.
FAO, 2024. The state of world fisheries and aquaculture 2024. Rome. URL. https://doi.org/10.4060/cd0683en.
Føre, H.M., Hatlebrekke, H.H., Grimaldo, E., 2023. Alternative rope materials in towed fishing gear to reduce plastic waste, a comparative study of mechanical properties and tolerance against Wear and tear, in: Volume 4: Ocean Space Utilization, American Society of Mechanical Engineers, Melbourne, Australia. p. V004T05A003. URL: https://asmedigitalcollection.asme.org/OMAE/proceedings/OMAE2023/86861/V004T05A003/1167107, doi: https://doi.org/10.1115/OMAE2023-104444.
Grimaldo, E., Herrmann, B., Jacques, N., Kubowicz, S., Cerbule, K., Su, B., Larsen, R., Vollstad, J., 2020a. The effect of long-term use on the catch efficiency of biodegradable gillnets. Mar. Pollut. Bull. 161, 111823. URL: https://www.sciencedirect.com/science/article/pii/S0025326X20309413 https://doi.org/10.1016/j.marpolbul.2020.111823.
Grimaldo, E., Herrmann, B., Jacques, N., Vollstad, J., Su, B., 2020b. Effect of mechanical properties of monofilament twines on the catch efficiency of biodegradable gillnets. PLoS One 15, e0234224. URL: https://dx.plos.org/10.1371/journal.pone.0234224 https://doi.org/10.1371/journal.pone.0234224.
Grimaldo, E., Herrmann, B., Su, B., Føre, H.M., Vollstad, J., Olsen, L., Larsen, R.B., Tatone, I., 2019. Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets. Fish. Res. 213, 67–74. https://www.sciencedirect.com/science/article/pii/S0165783619300037. https://doi.org/10.1016/j.fishres.2019.01.003.
Grimaldo, E., Herrmann, B., Tveit, G.M., Vollstad, J., Schei, M., 2018a. Effect of using biodegradable gill nets on the catch efficiency of Greenland halibut. Marine and coastal fisheries 10, 619–629. URL: https://afspubs.onlinelibrary.wiley.com/doi/full/10.1002/mcf2.10058, doi: https://doi.org/10.1002/mcf2.10058. Publisher: John Wiley & Sons, ltd.
Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe Føre, H., Larsen, R.B., Tatone, I., 2018b. Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (Gadus morhua) and saithe (Pollachius virens) fisheries. ICES J. Mar. Sci. 75, 2245–2256. URL: https://doi.org/10.1093/icesjms/fsy108, doi: https://doi.org/10.1093/icesjms/fsy108.
Grimaldo, E., Karl, C.W., Alvestad, A., Persson, A.M., Kubowicz, S., Olafsen, K., Hatlebrekke, H.H., Lilleng, G., Brinkhof, I., 2023. Reducing plastic pollution caused by demersal fisheries. Mar. Pollut. Bull. 196, 115634. https://linkinghub.elsevier.com/retrieve/pii/S0025326X2301069X. https://doi.org/10.1016/j.marpolbul.2023.115634.
Hanni, K., Pyle, P., 2000. Entanglement of pinnipeds in synthetic materials at south-east Farallon Island, California, 1976–1998. Mar. Pollut. Bull. 40, 1076–1081. https://doi.org/10.1016/S0025-326X(00)00050-3.
Hong, S., Lee, J., Lim, S., 2017. Navigational threats by derelict fishing gear to navy ships in the Korean seas. Mar. Pollut. Bull. 119, 100–105. https://www.sciencedirect.com/science/article/pii/S0025326X17303004. https://doi.org/10.1016/j.marpolbul.2017.04.006.
Hubert, W.A., Pope, K.L., Dettmers, J.M., 2012. Passive Capture Techniques. Fisheries Techniques 223–265.
Humborstad, O.B., Løkkeborg, S., Hareide, N.R., Furevik, D.M., 2003. Catches of Greenland halibut (Reinhardtius hippoglossoides) in Deepwater ghost-fishing gillnets on the Norwegian continental slope. Fish. Res. 64, 163–170. https://www.sciencedirect.com/science/article/pii/S0165783603002157. https://doi.org/10.1016/S0165-7836(03)00215-7.
Jang, M., Shim, W.J., Cho, Y., Han, G.M., Ha, S.Y., Hong, S.H., 2024. Hazardous chemical additives within marine plastic debris and fishing gear: occurrence and implications. J. Clean. Prod. 442, 141115. https://linkinghub.elsevier.com/retrieve/pii/S0959652624005626. https://doi.org/10.1016/j.jclepro.2024.141115.
Kim, I.O., Lee, G.H., 2014. Catching efficiency of biodegradable trap for swimming crab (Portunus trituberculatus) in the western sea of Korea. Journal of the Korean Society of Fisheries and Ocean Technology 50, 262–273. URL: http://koreascience.or.kr/article/JAKO201426636276546.page, doi: https://doi.org/10.3796/KSFT.2014.50.3.262. Publisher: the Korean Society of Fisheries and Ocean Technology.
Kim, J., Park, S., Jung, S., Yun, H., Choi, K., Heo, G., Jin, H.J., Park, S., Kwak, H.W., 2023. Biodegradation behavior of polybutylene succinate (PBS) fishing gear in marine sedimentary environments for ghost fishing prevention. Polymer degradation and stability 216, 110490. https://www.sciencedirect.com/science/article/pii/S0141391023002409. https://doi.org/10.1016/j.polymdegradstab.2023.110490.
Kim, J., Yun, H., Won, S., Lee, D., Baek, S., Heo, G., Park, S., Jin, H.J., Kwak, H.W., 2024. Comparative degradation behavior of polybutylene succinate (PBS), used PBS, and PBS/Polyhydroxyalkanoates (PHA) blend fibers in compost and marine–sediment interfaces. Sustainable. Mater. Technol. 41, e01065. https://www.sciencedirect.com/science/article/pii/S2214993724002458. https://doi.org/10.1016/j.susmat.2024.e01065.
Kim, S., Kim, P., Jeong, S., Bae, J., Lim, J., Oh, W., 2018. Fishing performance of a coastal drift net in accordance with materials of the environmentally-friendly biodegradable net twine. Journal of the Korean Society of Fisheries Technology 54, 97–106. http://ksft.or.kr/journal/article.php?code=61680. https://doi.org/10.3796/KSFOT.2018.54.2.097.
Kim, S., Kim, P., Lim, J., An, H., Suuronen, P., 2016. Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. Anim. Conserv. 19, 309–319. URL: https://onlinelibrary.wiley.com/doi/10.1111/acv.12256 https://doi.org/10.1111/acv.12256.
Le Gué, L., Davies, P., Arhant, M., Vincent, B., Tanguy, E., 2023. Mitigating plastic pollution at sea: natural seawater degradation of a sustainable PBS/PBAT marine rope. Mar. Pollut. Bull. 193, 115216. URL: https://www.sciencedirect.com/science/article/pii/S0025326X23006495 https://doi.org/10.1016/j.marpolbul.2023.115216.
Le Gué, L., Savina, E., Arhant, M., Davies, P., Dumergue, N., Vincent, B., 2024a. Influence of knot strength on the mechanical performance of a biodegradable gillnet. Sci. Rep. 14, 15450. URL: https://www.nature.com/articles/s41598-024-66474-3 https://doi.org/10.1038/s41598-024-66474-3.
Le Gué, L., Savina, E., Arhant, M., Davies, P., Gayet, N., Vincent, B., 2024b. Degradation mechanisms in PBSAT nets immersed in seawater. Polymer degradation and stability 225, 110788. https://linkinghub.elsevier.com/retrieve/pii/S0141391024001320. https://doi.org/10.1016/j.polymdegradstab.2024.110788.

Lebreton, L., Royer, S.J., Peytavin, A., Strietman, W.J., Smeding-Zuurendonk, I., Egger, M., 2022. Industrialised fishing nations largely contribute to floating plastic pollution in the North Pacific subtropical gyre. Scientific reports 12, 12666. URL: https://www.nature.com/articles/s41598-022-16529-0, doi: https://doi.org/10.1038/s41598-022-16529-0. Number: 1 Publisher: nature publishing group.
Limonta, G., Panti, C., Fossi, M.C., Nardi, F., Baini, M., 2024. Exposure to virgin and marine incubated microparticles of biodegradable and conventional polymers modulates the hepatopancreas transcriptome of Mytilus galloprovincialis. J. Hazard. Mater. 468, 133819. URL: https://linkinghub.elsevier.com/retrieve/pii/S0304389424003984 https://doi.org/10.1016/j.jhazmat.2024.133819.
Loubet, P., Couturier, J., Horta Arduin, R., Sonnemann, G., 2022. Life cycle inventory of plastics losses from seafood supply chains: methodology and application to French fish products. Sci. Total Environ. 804, 150117. URL: https://www.sciencedirect.com/science/article/pii/S0048969721051925 https://doi.org/10.1016/j.scitotenv.2021.150117.
Malafeev, K.V., Apicella, A., Incarnato, L., Scarfato, P., 2023. Understanding the impact of biodegradable microplastics on living organisms entering the food chain: a review. Polymers 15, 3680. URL: https://www.mdpi.com/2073-4360/15/18/3680, doi: https://doi.org/10.3390/polym15183680. Number: 18 Publisher: multidisciplinary digital publishing institute.
Matsushita, Y., Machida, S., Kanehiro, H., Nakamura, F., Honda, N., 2008. Analysis of mesh breaking loads in cotton gill nets: possible solution to ghost fishing. Fish. Sci. 74. https://doi.org/10.1111/j.1444-2906.2008.01517.x.
Morales-Caselles, C., Viejo, J., Martí, E., González-Fernández, D., Pragnell-Raasch, H., González-Gordillo, J.I., Montero, E., Arroyo, G.M., Hanke, G., Salvo, V.S., Basurko, O.C., Mallos, N., Lebreton, L., Echevarría, F., van Emmerik, T., Duarte, C. M., Gálvez, J.A., van Sebille, E., Galgani, F., García, C.M., Ross, P.S., Bartual, A., Ioakeimidis, C., Markalain, G., Isobe, A., Cózar, A., 2021. An inshore–offshore sorting system revealed from global classification of ocean litter. Nature Sustainability 4, 484–493. http://www.nature.com/articles/s41893-021-00720-8. https://doi.org/10.1038/s41893-021-00720-8.
Nguyen, T.X., Winger, P.D., 2016. Numerical modeling - a comparison of different methods for simulating bottom trawls. Fish. Technol. 53, 9–29.
O'Neill, F., Breddermann, K., 2024. The contribution of mesh opening angle to the drag of netting panels. Ocean Eng. 305, 117959. URL: https://linkinghub.elsevier.com/retrieve/pii/S0029801824012976 https://doi.org/10.1016/j.oceaneng.2024.117959.
Palmeiro-Sánchez, T., O'Flaherty, V., Lens, P.N.L., 2022. Polyhydroxyalkanoate bio-production and its rise as biomaterial of the future. J. Biotechnol. 348, 10–25. https://www.sciencedirect.com/science/article/pii/S0168165622000426. https://doi.org/10.1016/j.jbiotec.2022.03.001.
Park, S., Bae, B., Cha, B.j., Kim, Y.J., Kwak, H.W., 2023. Development of poly(butylene adipate-co-butylene succinate-co-ethylene adipate-co-ethylene succinate) (PBEAS) net twine as biodegradable fishing gear. Mar. Pollut. Bull. 194, 115295. https://linkinghub.elsevier.com/retrieve/pii/S0025326X23007294. https://doi.org/10.1016/j.marpolbul.2023.115295.
Paul-Pont, I., Ghiglione, J.F., Gastaldi, E., Ter Halle, A., Huvet, A., Bruzaud, S., Lagarde, F., Galgani, F., Duflos, G., George, M., Fabre, P., 2023. Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life. Waste Manag. 157, 242–248. https://www.sciencedirect.com/science/article/pii/S0956053X22006158. https://doi.org/10.1016/j.wasman.2022.12.022.
Queirolo, D., DeLouche, H., Hurtado, C., 2009. Comparison between dynamic simulation and physical model testing of new trawl design for Chilean crustacean fisheries. Fish. Res. 97, 86–94. https://linkinghub.elsevier.com/retrieve/pii/S0165783609000198. https://doi.org/10.1016/j.fishres.2009.01.005.
Ramp, C., Gaspard, D., Gavrilchuk, K., Unger, M., Schleimer, A., Delarue, J., Landry, S., Sears, R., 2020. Up in the air: drone images reveal underestimation of entanglement rates in large rorqual whales. Endanger. Species Res. 44. https://doi.org/10.3354/esr01084.
Richards, S., Bouazza, A., 2007. Determination of particle density using water and gas pycnometry. Géotechnique 57, 403–406. URL: https://www.icevirtuallibrary.com/doi/full/10.1680/geot.2007.57.4.403, doi: https://doi.org/10.1680/geot.2007.57.4.403. publisher: ICE Publishing.
Richardson, K., Gunn, R., Wilcox, C., Hardesty, B.D., 2018. Understanding causes of gear loss provides a sound basis for fisheries management. Mar. Policy 96, 278–284. https://linkinghub.elsevier.com/retrieve/pii/S0308597X17307406. https://doi.org/10.1016/j.marpol.2018.02.021.
Richardson, K., Hardesty, B.D., Wilcox, C., 2019. Estimates of fishing gear loss rates at a global scale: a literature review and meta-analysis. Fish Fish. 20, 1218–1231. https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12407. https://doi.org/10.1111/faf.12407.
Richardson, K., Wilcox, C., Vince, J., Hardesty, B.D., 2021. Challenges and misperceptions around global fishing gear loss estimates. Mar. Policy 129, 104522. URL: https://www.sciencedirect.com/science/article/pii/S0308597X21001330 https://doi.org/10.1016/j.marpol.2021.104522.
Rousseau, Y., Blanchard, J.L., Novaglio, C., Pinnell, K.A., Tittensor, D.P., Watson, R.A., Ye, Y., 2024. A database of mapped global fishing activity 1950–2017. Scientific Data 11, 48. https://www.nature.com/articles/s41597-023-02824-6. https://doi.org/10.1038/s41597-023-02824-6.
Ryan, P.G., 2018. Entanglement of birds in plastics and other synthetic materials. Mar. Pollut. Bull. 135, 159–164. https://linkinghub.elsevier.com/retrieve/pii/S0025326X18304624. https://doi.org/10.1016/j.marpolbul.2018.06.057.
Savina, E.A.C.M., Bertelsen, I.M.G., Cerbule, K., Le Gué, L., Herrmann, B., Krag, L.A., 2024. Can operational tactics compensate for weaker tensile properties of biodegradable gillnets? Canadian journal of fisheries and aquatic sciences URL: https://cdnsciencepub.com/doi/10.1139/cjfas-2024-0094, doi: https://doi.org/10.1139/cjfas-2024-0094. Publisher: NRC research press.
Sekiguchi, T., Saika, A., Nomura, K., Watanabe, T., Watanabe, T., Fujimoto, Y., Enoki, M., Sato, T., Kato, C., Kanehiro, H., 2011. Biodegradation of aliphatic polyesters soaked in deep seawaters and isolation of poly(e-caprolactone)-degrading bacteria. Polymer degradation and stability 96, 1397–1403. https://www.sciencedirect.com/science/article/pii/S014139101100108X. https://doi.org/10.1016/j.polymdegradstab.2011.03.004.
Seonghun, K., Park, S., Lee, K., 2014. Fishing performance of an Octopus minor net pot made of biodegradable twines. Turk. J. Fish. Aquat. Sci. 14, 21–30. https://doi.org/10.4194/1303-2712-v14_1_03.
Sharma, D., Dhanker, R., Bhawna, Tomar, A., Raza, S., Sharma, A., 2024. Fishing gears and nets as a source of microplastic, in: Shahnawaz, M., Adetunji, C.O., Dar, M.A., Zhu, D. (Eds.), Microplastic Pollution. Springer Nature, Singapore, pp. 127–140. URL: https://doi.org/10.1007/978-981-99-8357-5_8, doi: https://doi.org/10.1007/978-981-99-8357-5_8.
Stelfox, M., Hudgins, J., Sweet, M., 2016. A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. Mar. Pollut. Bull. 111, 6–17. https://www.sciencedirect.com/science/article/pii/S0025326X16304386. https://doi.org/10.1016/j.marpolbul.2016.06.034.
Suzuki, M., Tachibana, Y., Kasuya, K.i., 2021. Biodegradability of poly(3-hydroxyalkanoate) and poly(ε-caprolactone) via biological carbon cycles in marine environments. Polym. J. 53, 47–66. https://www.nature.com/articles/s41428-020-00396-5. https://doi.org/10.1038/s41428-020-00396-5 (bandiera_abtest: a Cc_license_type: cc_by Cg_type: Nature Research Journals Number: 1 Primary_atype: Reviews Publisher: Nature Publishing Group Subject_term: Ecology;Microbiology Subject_term_id: ecology;microbiology).
Thierry, N.N.B., Tang, H., Achile, N.P., Xu, L., Hu, F., You, X., 2020. Comparative study on the full-scale prediction performance of four trawl nets used in the coastal bottom trawl fishery by flume tank experimental investigation. Appl. Ocean Res. 95, 102022. URL: https://www.sciencedirect.com/science/article/pii/S0141118719305814 https://doi.org/10.1016/j.apor.2019.102022.
Valderrama Ballesteros, L., Matthews, J.L., Hoeksema, B.W., 2018. Pollution and coral damage caused by derelict fishing gear on coral reefs around Koh Tao, gulf of Thailand. Mar. Pollut. Bull. 135, 1107–1116. https://linkinghub.elsevier.com/retrieve/pii/S0025326X18305976. https://doi.org/10.1016/j.marpolbul.2018.08.033.
Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499. https://www.sciencedirect.com/science/article/pii/S0269749113004387. https://doi.org/10.1016/j.envpol.2013.08.013.
Vincent, B., 2000. A New Generation of Tools for Trawls Dynamic Numerical Simulation, in: Contributions on the Theory of Fishing Gears and Related Marine Systems. Neuer Hochschulschriftenverl, Rostock.
Vincent, B., Robert, M., Simon, J., Vacherot, J., Faillettaz, R., 2022. Exploring the mechanics of fish escape attempts through mesh. Fish. Res. 248, 106195. https://linkinghub.elsevier.com/retrieve/pii/S0165783621003234. https://doi.org/10.1016/j.fishres.2021.106195.
Vincent, B., Roullot, J., 2006. Towed Gear Optimisation, Application to Trawls. Brussels.
Vincent, B., Simon, J., Di Cesare, N., 2020. Development of a model for flexural rigidity of fishing net with a spring mass approach and its inverse identification by metaheuristic parametric optimization. Ocean Eng. 203, 107166. URL: https://linkinghub.elsevier.com/retrieve/pii/S0029801820302250 https://doi.org/10.1016/j.oceaneng.2020.107166.
Wang, G., Huang, D., Ji, J., Völker, C., Wurm, F.R., 2021. Seawater-degradable polymers—fighting the marine plastic pollution. Advanced. Science 8, 2001121. https://onlinelibrary.wiley.com/doi/10.1002/advs.202001121. https://doi.org/10.1002/advs.202001121.
Winger, P., DeLouche, H., Legge, G., 2006. Designing and testing new fishing gears: the value of a flume tank. Mar. Technol. Soc. J. 40, 44–49. https://doi.org/10.4031/002533206787353240.
Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492. https://www.sciencedirect.com/science/article/pii/S0269749113001140. https://doi.org/10.1016/j.envpol.2013.02.031.
Yoshida, K., Teramoto, S., Gong, J., Kobayashi, Y., Ito, H., 2024. Enhanced marine biodegradation of Polycaprolactone through incorporation of mucus bubble powder from Violet Sea snail as protein fillers. Polymers 16, 1830. URL: https://www.mdpi.com/2073-4360/16/13/1830, doi: https://doi.org/10.3390/polym16131830. Number: 13 Publisher: multidisciplinary digital publishing institute.
Yu, M., Tang, Y., Min, M., Herrmann, B., Cerbule, K., Liu, C., Dou, Y., Zhang, L., 2023. Comparison of physical properties and fishing performance between biodegradable

PLA and conventional PA trammel nets in grey mullet (Mugil cephalus) and red-lip mullet (Liza haematocheila) fishery. Mar. Pollut. Bull. 195, 115545. https://linkinghub.elsevier.com/retrieve/pii/S0025326X23009803. https://doi.org/10.1016/j.marpolbul.2023.115545.
Zimmermann, L., Dombrowski, A., Völker, C., Wagner, M., 2020. Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition. Environ. Int. 145, 106066. https://www.sciencedirect.com/science/article/pii/S0160412020320213. https://doi.org/10.1016/j.envint.2020.106066.
Zobell, C.E., Conn, J.E., 1940. Studies on the thermal sensitivity of marine Bacteria. J. Bacteriol. 40, 223–238. URL: https://journals.asm.org/doi/10.1128/jb.40.2.223-238.1940, doi: https://doi.org/10.1128/jb.40.2.223-238.1940.
Žydelis, N., Dagys, M., Vaitkus, G., 2006. Beached bird surveys in Lithuania reflect marine oil pollution and bird mortality in fishing nets. Mar. Ornithol. 34, 161–166.