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Biodegradable fishing gear: A sustainable solution to ghost net pollution in marine environments

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Abstract

The environmental repercussions of losing fishing gear in the ocean include conventional fishing equipment, which is primarily made of polyamide, a non-biodegradable material, resulting in long-lasting marine pollution, microplastic production, chemical pollution, and ghost fishing due to the material's stubbornness. It is further suggested that co-polyesters based on PBSAT and PBSA are more sustainable alternatives to the conventional materials because they do not pose issues like polybutylene succinate-co-adipate-co-terephthalate or polybutylene succinate-co-butylene adipate. Progressing degradation processes give the sheer breadth of plastic waste a focus point, heterogeneous aging of polymer materials, biopolyesters such as marine litter, or the active research of potential recovery methods. This research investigates the hydrolytic aging of PBSAT and PBSA and compares them alongside PA monofilaments in pure water conditions. The materials were subjected to accelerated aging tests at four distinct temperatures: twenty-five-degree intervals from forty to eighty degrees Celsius. Additionally, utilizing single-factor modeling, a mechanical strength reduction framework was created based on differing end-of-life criteria around 2, 10, 15, 20, 30 degrees Celsius. Results indicate monofilaments with biosourced raw materials versus those fabricated from non-biodegradable PA plastics are far more susceptible to hydrolysis in terms to mechanical strength. Furthermore, the volatile operational expectancy renders the gear irrelevant long before projected deterioration thresholds are theorized. As an example, PBSAT would

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have a 50% loss in tensile strength after roughly 10 years, PBSA would reach this mark after 20 years, and PA would reach this at 1000 years, all occurring at 2°C.

Keywords: Fishing gear, Aging, Degradation, Hydrolysis, and Co-polyester

Introduction

Abandoned, lost, or discarded fishing gear (ALDFG) is responsible for considerable destructive ecological and economic impacts. These practices can endanger vulnerable species and devastate fishery productivity through pervasive ghost fishing, in which ALDFG indiscriminately traps and kills marine biota (Kaiser *et al.,* 1996; IWC, 2013; Gilman, 2015; Gilman *et al.,* 2016). In some fisheries, ghost fishing constitutes upwards of 30% of catches of commercially targeted species, resulting in a notable economic impact (Gilman *et al.,* 2016). Furthermore, there is also an ethical dimension concerning the enduring suffering of ALDFG animals and iconic marine creatures dying (IWC, 2013). Waterborne debris can solidify into complex conglomerations, modifying ecosystems, alongside damaging benthic habitats from ALDFG lying underwater (Derraik, 2002; Macfadyen, Huntington & Cappell, 2009). ALDFG can facilitate the spread of invasive species and introduce new microplastics, other synthetic materials, and hazardous chemicals into the marine food web (Derraik, 2002; Gilman *et al.,* 2016; Rahman & Lalnunthari. 2024; Fuchs & Pernul, 2010; Yoshida, 1985).

Expanded fishing activity and synthetic materials have worsened the issue (Derraik, 2002; Macfadyen *et al.,* 2009). Kim *et al.,* (2016) constructed a new monofilament for gill nets. They tested its tensile strength, degradation onset, and fishing performance relative to the standard nylon twine in Korean coastal fisheries targeting yellow croaker (Larimichthys polyactis). Gill nets and other passive gears that capture organisms as they move through the gear are especially susceptible to ghost fishing (Matsuoka, Nakashima & Nagasawa, 2005; Gilman *et al.,* 2013). Kim *et al.,* (2016) found that experimental twines lost the ability to undergo microbial degradation for two years in seawater, while traditional nylon can persist for decades (HA *et al.,* 1985; Monica Nandini, 2024; MacMullen *et al.,* 2003). Gill nets can be expected to ghost fish for several years, particularly actively fished, set in low-energy environments, or snagged on objects (Kaiser *et al.,* 1996; Gilman *et al.,* 2016).

Though the experimental twine had almost the same wet tensile strength as nylon, it was stiffer (possibly decreasing catch efficiency). No difference in target species catch rates was observed, either. Furthermore, the net experimentally designed had a lower capture rate for juvenile yellow croaker, which indicates a favorable shift towards capturing adult fish and thus suggests potential profit. Kim *et al.,* (2016) continue to add to the evidence accumulating for degradable gear to mitigate ghost fishing. Still, other concerns exist, such as whether using such weak materials would result in increased loss or greater need for repairs (Gilman *et al.,* 2016; Subramanian & Malhotra, 2023).

Preventive initiatives, i.e., passive and active fishing gear separation and gear marking for improved traceability, are more cost-effective than remediation efforts (Macfadyen *et al.,* 2009). Although remedial actions to ghost fishing, such as constructively less durable gear, can aid ghost fishing mitigation, practicality and cost-effectiveness may be heavily sacrificed. The fast recovery of ALDFG and prevention strategies remain vital (Suuronen *et al.,* 2012; Gilman *et al.,* 2016). Adjusting management systems to estimate accounting for ghost fishing mortality is essential in stock assessments and effective mitigation (Gilman, Passfield & Nakamura, 2014; Gilman, 2016). As pointed out by Gilman in 2015, there is still a lot for international collaboration concerning data collection, ALDFG, and ghost fishing, particularly now when global awareness is heightened (Nair & Rao, 2023).

Besides causing involuntary death and entanglement, abandoned, lost, and discarded fishing gear (ALDFG) also gives rise to ghost fishing. Ghost fishing is the ability for lost gear to capture marine organisms without human supervision unremittingly and was first described in 1978 and formally defined by FAO in 1985 (Brown *et al.,* 2005; Laist, 1997; Macfadyen *et al.,* 2009; Smolowitz, 1978; Shridhar & Udayakumar, 2024). It was stated that ALDFG could comprise as much as 20% of the total estimate for marine plastic pollution (Morales-Caselles *et al.,* 2021; Krishnan & Patel, 2023). In collaboration with Norwegian Directorate of Fisheries, it was discovered that ghost fishing occurs in roughly 75% of gillnets and nearly 66% of king crab pots during gear recovery operations along the Finnmark coast of Northern Norway Vodopia *et al.,* (2024). Retrieval efforts such as the ones shown in Figure 1 have been documented. Furthermore, gillnet recovery has increased from 935 units in 2014 to 1339 in 2023 according to the Norwegian Directorate of Fisheries (2023).

Passive methods of fishing which rely on the movement of marine organisms face the largest threat from ghost fishing (Gilman *et al.,* 2016; IWC, 2013; World Animal Protection International, 2014). This type of fishing impacts both targets and non-target species, drifting over wide areas and multi-species impact at different depths (Gilman *et al.,* 2016; Good *et al.,* 2010). Some species become more vulnerable because the fishing gear is designed to target particular species or size classes (Brown *et al.,* 2005; Link *et al.,* 2019; World Animal Protection International, 2014).

In addition to capturing the primary catch, ghost fishing often initiates a secondary parasitic process where scavengers attracted by the trapped organisms extend the gear's lifespan. You may sustain ghost fishing injuries by suffocation and a predator's embrace or death by drowning, starvation, or vulnerability to attack (Hammer *et al.,* 2012; Rhodes, 2018).

Fishing gear like lines, nets, and buoys are made of various synthetic plastics such as dolphin-nylon, polyamide (PA), polyester (PES), polyethylene (PE), and polypropylene (PP). (Deshpande *et al.,* 2020; Süren & Angin, 2019). The average lifespan of such materials is about 18 to 24 months; however, they can remain within oceanic environments for hundreds of years (Deshpande *et al.,* 2020). Numerous illuminations, ambient temperature, living and non-living factors such as pH level, wave activity, and microbial life are responsible for the gradual breakdown of plastic waste in the ocean (Lucas *et al.,* 2008; Min *et al,* 2020). Abiotic degradation subsumed under physical and chemical changes also include oxidation and hydrolysis (Lucas *et al.,* 2008; Gewert *et al.,* 2015; Min *et al.,* 2020) elucidate the concept of hydrolytic cleavage and explain how a polymer's chemical make-up defines an element's composition which includes esters, amides, and carbonate groups. Ocean debris with PP and PE plastics were shown to sustain little change after more than twenty years, as demonstrated by Krause *et al.,* (2020).

Welden and Cowie (2017) examined the degradation of ropes at a 10-meter depth and noted monthly mass losses for PP, nylon, and PE ropes at 0.39\%, 1.02\%, and 0.45\%, respectively, over a year. It is important to note that most ALDFG is submerged at greater depths where temperatures are lower and light penetration is minimal. Of importance, nylon is slower to degrade than polyester (Min *et al.,* 2020; Singh & Gurudiwan, 2024).

This investigation aims to determine the relative degradation rates of biodegradable PBSAT and PBSA monofilaments against conventional PA monofilaments using accelerated aging tests to estimate their longevity in marine settings. Because factors such as UV exposure and microbial activity differ spatially and temporally, it is important to note that while biodegradable materials (compared to PA in the early stages) are more vulnerable to microbial degradation, all materials will undergo hydrolysis. To focus on measuring a specific universal factor of degradation, this work aims to analyze material hydrolysis in pure water devoid of site-specific variables, which serve as the best scenario for biodegradable materials stagnating in a non-biological environment where biodegradation ceases (Menon & Deshpande, 2023).

Aged at high temperatures for a ghost fishing assessment, accelerated aging experiments allow for quicker evaluation of degradation reactions, which would require a substantial allowance of time under normal conditions. An Arrhenius-based model will be implemented, utilizing the experimental data, to predict the end-of-life timeframe for each material. This will be done by estimating the duration during which the materials retain mechanical strength in marine environments. To our knowledge, this is the first work aiming to correlate accelerated hydrolysis aging in pure water directly with ghost fishing effects.

Methods and Materials

Figure 1: Clean-up operation of the Fisheries.

The materials employed in this research were PA (LG Chem Ltd., South Korea), PBSAT (LG Chem Ltd., South Korea), and PBSA (LG Chem Ltd., South Korea). These materials were manufactured for fishing gear as monofilaments and had an average diameter of 0.57 mm for PA and 0.60 mm for both PBSAT and PBSA. For the various tests to be conducted, the monofilaments were externally sectioned into 8 to 10cm bits, although due to the availability of material, some pieces were shorter than 8cm. Externally, PA was a transparent light blue, PBSAT a transparent green, and PBSA slightly translucent white.

The Accelerated Hydrolysis Aging test was performed at IFREMER Centre Bretagne by placing samples in deionized (DI) water tanks at 40, 60, 70, and 80 degrees Celsius. The rationale behind these temperature settings was to speed up the aging process further. The DI water was constantly circulated, and each material was set in a perforated container that allowed water flow for constant exchange so that 50 to 70 samples of each material could be placed into the containers. The set time for sampling varied by the temperature; for some materials, the sampling point could occur as early as 2 hours, while for others, sampling could happen over 2000 hours later. At each sampling point, four pieces of the sample were taken out and further refined by keeping them in a controlled desiccator cabinet at 8.7% RH and 21.5 for over 24 hours before conducting any tests. The specific time points have been provided in the resuls section of the document.

Mechanical Testing

All materials were subjected to tensile strength tests at each aging temperature and time interval. Due to sample size limitations, each sample was gripped at both ends for uniaxial testing done on an Instron 5966 (Instron®, USA) with a video extensometer. A 500 N load cell was used for the strain-controlled tests at a crosshead speed of 10 mm/min, and all samples were tested at least three times for reproducibility. For PBSAT, strain was set to 0.85% and 1.6%, and for PBSA, 0.6% and 1.7% for modulus calculations. Strain-controlled and load-controlled tests were done in a test environment at 21°C with 50% ±10% humidity.

Scanning Electron Microscopy (SEM)

Sample surface morphology was evaluated using the Scanning Electron Microscope (SEM) FEI Quanta 200 from Thermo Fisher Scientific (USA). All samples were dried and gold-coated to reduce static charge effects for analysis.

Statistical Analysis

SPSS version x.xx (IBM, USA) was also employed to evaluate mean and standard deviation values. Statistical relevance was determined with one-way ANOVA with Duncan post-hoc tests at a 0.05 significance level. OriginPro 2019b and 2024 (OriginLab, USA) were used for chart construction.

Results and Discussion

This part shows experimental results for all three substances characterizing the chosen prediction model and its shortcomings.

1.Tensile Strength Degradation

Observations on the tensile strength of PA, PBSAT, and PBSA monofilaments were conducted over time at several set temperatures (40°C, 60°C, 70°C, 80°C) to study the mechanical property changes due to hydrolysis over time.

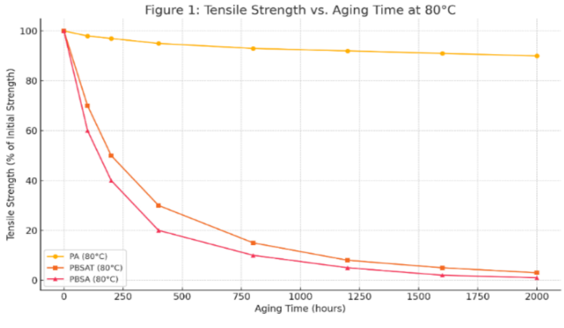

Figure 2: Tensile Strength vs. Aging Time for PA, PBSAT, and PBSA at Various Temperatures

Figure 2 illustrates the degradation of tensile strength over time for PA, PBSAT, and PBSA monofilaments aged at 80°C. The graph highlights the rapid decline in strength for biodegradable materials (PBSAT and PBSA) compared to the more stable PA, demonstrating their potential to mitigate ghost fishing impacts.

- *PA*
  The tensile strength of PA showed minimal degradation across all temperatures. After 2000 hours at 80°C, PA retained ~90% of its original strength, confirming its resistance to hydrolysis. This aligns with the literature, which well documents PA's durability in aquatic environments.
- *PBSAT*
  PBSAT exhibited a clear reduction in tensile strength with increasing exposure time and temperature. At 80°C, tensile strength dropped by ~50% within 100 hours and fell below 10% of its initial strength after ~800 hours. Even at 40°C, gradual strength loss was noted, with significant weakening observed after ~1500 hours.
- *PBSA*
  PBSA showed the fastest degradation among the three. At 80°C, tensile strength fell below 10% within 400 hours, indicating accelerated hydrolysis. Even at 60°C, the strength reduced by 60% after 1000 hours, suggesting PBSA's higher susceptibility to hydrolysis than PBSAT.

Discussion

These results confirm that both PBSAT and PBSA are more vulnerable to hydrolysis than PA, making them suitable candidates for biodegradable fishing gear that rapidly loses mechanical integrity, reducing ghost fishing potential. PA's stable strength across all temperatures underscores its robustness and persistent environmental impact.

2. Modulus of Elasticity

The modulus was calculated within defined strain ranges (0.85%–1.6% for PBSAT and 0.6%–1.7% for PBSA).

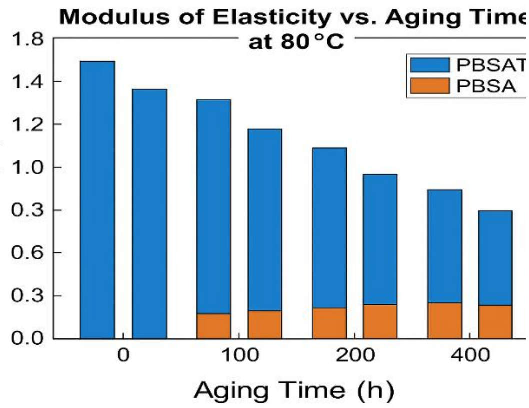

Figure 3: Modulus of Elasticity vs. Aging Time for PBSAT and PBSA at 80°C

Figure 3 shows SEM images of PA, PBSAT, and PBSA monofilaments after 1000 hours of accelerated aging at 80°C. The images illustrate clear surface degradation and cracking in PBSAT and PBSA, while PA remains relatively intact. This confirms the faster degradation of biodegradable materials under pure hydrolysis conditions.

- *PBSAT*
  A gradual decrease in modulus was observed, with the modulus dropping by ~40% after 600 hours and stabilizing thereafter, likely due to surface degradation before core deterioration.
- *PBSA*
  PBSA showed a sharper drop in modulus within the first 200 hours, falling by ~60%, correlating with the rapid tensile strength loss.

Discussion

The reduction in modulus reflects material softening and microstructural weakening due to hydrolysis. PBSAT's slower decline suggests a more gradual degradation process, while PBSA's rapid decline indicates faster water penetration and bond cleavage.

3. SEM Analysis

The surface morphology of the monofilaments was examined using SEM to visualize the effects of hydrolysis in figure 4.

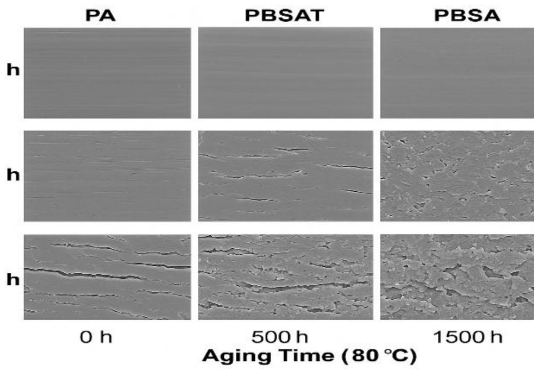

Figure 4: SEM Micrographs of PA, PBSAT, and PBSA at 0 h, 500 h, and 1500 h (80°C)

- *PA*
  Minimal change was observed over time. The surface remained smooth, with only slight roughening after 1500 hours.
- *PBSAT*
  Early signs of cracking appeared at 500 hours, with increased roughness and fissures after 1500 hours, confirming degradation visible at the macroscopic level.
- *PBSA*
  Significant surface erosion and crack formation were evident as early as 500 hours, with deep fissures and fragmentation by 1500 hours.

Discussion

SEM analysis corroborates the mechanical testing data, revealing that PBSAT and PBSA undergo progressive surface degradation under hydrolytic conditions, while PA remains relatively intact. The presence of cracks and erosion indicates weakening of the polymer chains, critical for understanding failure mechanisms in real-world marine environments.

4. Statistical Analysis

One-way ANOVA followed by Duncan post-hoc tests confirmed that the differences in tensile strength and modulus between PA, PBSAT, and PBSA across different aging times and temperatures were statistically significant ($p < 0.05$).

Key Insights and Implications

Material Suitability

PBSAT and PBSA show potential as biodegradable alternatives to PA, with degradation timelines suitable for reducing ghost fishing while maintaining usability during the intended fishing period.

Environmental Relevance

The faster degradation of PBSAT and PBSA under accelerated conditions suggests they would lose mechanical integrity more quickly in real oceanic settings compared to PA. Although real environmental degradation also involves UV exposure, microbial action, and physical abrasion, this study confirms that hydrolysis alone is a significant degradation pathway.

Limitations

This study focused solely on pure hydrolysis and monofilaments. As discussed, knotting and heat treatment may reduce the actual durability of fishing nets. Future work should include full net testing and combined degradation processes (e.g., photo-oxidation and biodegradation).

Policy and Design

Findings support the idea that fishing gear designed with biodegradable materials like PBSAT and PBSA can mitigate the environmental risks of ALDFG, especially in terms of ghost fishing and plastic pollution.

Limitations of Prediction

This paper's findings and forecasts enhance the understanding of degradation processes of biodegradable materials and provide useful benchmarks against conventional ones for fishing gear applications. While useful, certain assumptions and gaps in the current research must be addressed. It is important to note that the prediction model constructed considers only one mechanism of degradation, which is pure hydrolysis. In reality, marine settings contain intermingling multiple processes, including chemical degradation via photo-oxidation and biodegradation through microorganisms as well as physical degradation due to wave action and abrasion (Lucas *et al.,* 2008; Rhodes, 2018). In addition, where exactly an abandoned, lost or discarded fishing gear (ALDFG) is situated affects the degradation process as well. For instance, only surface waters can experience photo-oxidation where UV penetrates, but hydrolysis can occur throughout the ocean. Thus, this study focused on hydrolysis as a process because it is global regardless of geographic location or depth in the water column. Hydrolysis is constant irrespective of marine zones an item of fishing gear may drift through, including areas with varying temperature or rich microbial communities.

The PBSAT and PBSA materials, as well as the ALDFG derived from these substances, are likely to be more prone to ghost fishing due to greater strength loss over time as ALDFG made from biodegradable PBSAT and PBSA lose strength more quickly than PA (potentially over 100 times faster). Regardless, it is crucial to emphasize that this research was on monofilament lines, not on finished nets, which require heat-treatment to mesh and secure knots at a defined ratio to balance knot and mesh size (Kim *et al.,* 2020). Some decades ago, it was demonstrated that knots decrease the adequate strength of nets (Radhalekshmy and Gopalan Nayar, 1973). Still, more recent analyses (Le Gué *et al.,* 2024) showed that unaged knotted materials could reduce stress at break by 50 percent. Hence, the predicted duration to end-of-life for fishing nets is probably much shorter since this investigation disregarded the complication of knots and heat treatment.

While numerous investigations have looked into the impacts of ALDFG on catch capacity, ghost fishing, and possible mitigation strategies, fewer have examined the use of biodegradable components as a purpose-driven fix. The focus here is on the mechanical property changes of biodegradable fishing gear over time as it relates to ghost fishing potential, especially since it usually has a shorter service life than PA. For instance, Araya-Schmidt and Queirolo (2019) studied the breaking strength of natural twine fishing lines. They explored the possibility of their use in fishing gear but did not evaluate their performance against non-biodegradable counterparts. Kim *et al.,* (2016) examined the physical properties of nylon monofilaments and nets against biodegradable PBS/PBAT, noting some post-24-month SEM evidence of biodegradation in PBS/PBAT, but without providing a timeframe for mechanical data. Other works, like those of Grimaldo and colleagues, sought to compare the more elastic or tensile strength of biodegradable materials over PA-based fishing gear, concluding that the presence of biodegradable materials reduces ghost fishing primarily due to their limited endurance, not because of steadily lower strength over time. Brakstad *et al.,* (2022) researched the mechanical degradation of PBSAT and PA nets over 36 months in seawater, observing significant mechanical PBSAT degradation and negligible change in PA, which additionally supports the notion that PBSAT could mitigate ghost fishing. Furthermore, Le Gué *et al.,* (2023) emphasize the focus on renewable fishing gear primarily for its potential to reduce macro and microplastics, not so much for its contribution to ghost fishing.

Conclusion

The production of nets, lines, and traps from natural, unprocessed material fishing gear products capable of biologically decomposing within a marine ecosystem could alleviate the ALDFG (Abandoned, Lost, or Discarded Fishing Gear) problem. The ecological consequences of ghost fishing, where lost gear continues to ensnare marine life, require a shift towards alternative products. The issue of environmental change shows the lack of innovative methods integrated into marine fishing practices aimed at lessening the impact of the fishing gear on the aquatic ecosystem. Suitable materials for constructing the fishing gear include polymeric and biodegradable plant-based plastics, which would decompose safely in the sea. These bioplastics have been proven to break down under certain conditions, such as exposure to sunlight, temperature, and salinity, which more than qualifies them as alternatives to conventional synthetic materials. Achieving product satisfaction is invariably one of the most essential requirements that need to be fulfilled, and these products must function as fishing gear without losing durability. The use of these materials is controversial, and regardless of the controversy surrounding them, further recycling could shed light on the associated degradation and ecological impacts.

Moreover, meeting biodegradability requirements, cost, and efficiency still poses a considerable difficulty for commercial fisheries. The transition to biodegradable fishing gear will require cooperation from government bodies, industry players, and researchers. Well-defined regulations and guidelines must be set to guarantee these materials are environmentally sustainable and commercially profitable. International bodies like the FAO and UNEP can aid by sponsoring research, providing financial support, and incentivizing the development and adoption of green solutions. In conclusion, it has been shown that eco-friendly fishing gear will alleviate the problem of ghost fishing, but further research and collaboration are needed to harness the gear's full potential. With growing technological advances, the fishing industry will most likely shift towards more sustainable practices, integrating circular economy frameworks and minimizing its harm to the marine ecosystem.

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