

Review

Properties and Recyclability of Abandoned Fishing Net-Based Plastic Debris

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Abstract: Plastics in marine environments undergo molecular degradation via biocatalytic and photocatalytic mechanisms. Abandoned, lost, or discarded fishing gear (ALDFG) damages marine and coastal environments as well as plant and animal species. This article reviews ghost fishing, ecological damage from marine plastics, recommended recycling practices and alternative usages of derelict fishing gear. Material mixing techniques are proposed to counteract the effect of biocatalytic and photocatalytic biodegradation within the context of plastic fish net recycling. There is a need for a new and rapid “multidimensional molecular characterization” technology to quantify, at a batch level, the extent of photocatalytic or biocatalytic degradation experienced on each recovered fishing net, comprising molecular weight alteration, chemical functional group polydispersity and contaminant presence. Rapid multidimensional molecular characterization enables optimized conventional material mixing of recovered fishing nets. In this way, economically attractive social return schemes can be introduced for used fishing nets, providing an economic incentive for fishers to return conventional fishing nets for recycling.

Keywords: ghost fishing; fish net recycling; material blending; multidimensional; molecular; characterization



Citation: Koziol, A.; Paso, K.G.; Kuciel, S. Properties and Recyclability of Abandoned Fishing Net-Based Plastic Debris. *Catalysts* **2022**, *12*, 948. <https://doi.org/10.3390/catal12090948>

Academic Editors: Simona M. Coman, Madalina Tudorache and Elisabeth Egholm Jacobsen

Received: 18 July 2022

Accepted: 24 August 2022

Published: 26 August 2022

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1. Introduction

Marine litter has been defined as ‘any persistent, manufactured or processed solid material discarded, disposed or abandoned in the marine environment [1]. It was estimated that the total amount of plastic that has been produced between 1950 and 2017 equals approx. 9.2 billion tons. Specifically, more than half of this plastic has been produced since 2004 and less than 10% of it has been recycled [2]. The general amount of plastic debris in the ocean varies. However, it has been estimated that on average, around 300,000 items of plastic debris are present per km² of ocean surface [3].

It is important to notice that plastic domination of marine litter occurs because of its longevity and density—some plastic types, like, for example, polypropylene, are less dense than seawater or, like polyester, are slightly denser. Among plastic waste in the ocean, it was indicated by the US National Marine Debris Monitoring Program that 17.7% of plastic litter found on beaches came from ocean fishing activity [4]. Taking into consideration abandoned, lost or discarded fishing gear’s (ALDFG) behavior and impact on ocean habitats, it is considered one of the greatest threats to ocean biodiversity.

It has been estimated that in 2018, global fish production will exceed 179 million tons. Unfortunately, this great number is directly connected to the increasing amount of ALDFG compared to the other components of marine debris. Every year, the global fishing gear losses include 5.7% of all fishing nets, 8.6% of all traps and 29% of all lines used [5]. This is why the majority of plastic waste was ALDFG, with 37% of fishing lines and 34% of fishing nets [6].

Habitat degradation due to plastic debris has a far-reaching impact on ocean biodiversity. The movement of plastic litter by tides and storms can result in severe physical damage to marine habitats and animals. Floating plastic is able to carry life-threatening bacteria and transport pharmaceuticals and toxins into coastal areas. The plastic may also contain several other chemicals and toxins added during the production process [2]. Plastic accumulated in water is often interpreted as food by marine animals. This will intoxicate their bodies. Many of these fish contaminated by plastic will eventually be consumed by people. Additionally, plastic debris that is passively moved by tides and wind transports non-indigenous species to new locations where they can become invasive and endanger local fauna and flora [2].

Plastic enters the ocean through several pathways. Mainly from rivers, directly from the land, and to a lesser extent, the input is atmospheric or biological. For example, birds that consume plastic particles on the land and excrete them into the ocean. However, the amount of plastic transported this way is smaller compared to other paths [7]. It is predicted that annual plastic flow to the oceans will nearly triple between 2016 and 2040. Additionally, more than 1000 rivers are responsible for 80% of the annual release of plastic, with small urban rivers being the most polluting. It has been estimated that the input from rivers ranges between 0.8 and 2.7 million tons per year [8]. Moreover, the annual direct input from the industry since 1950 has been estimated to be between 108 and 480 million tons [9].

It has been estimated that from 1.15 to 2.41 million tons of plastic enter the ocean every year. More than half of this plastic is less dense than water. This means that over 50% of this plastic is not going to sink to the seabed but will float closer to the surface once it enters the sea [10]. Buoyant plastic is transported by converging over extended distances and finally accumulating in the path. Once plastic particles enter the gyre, they are unlikely to leave until full degradation. More and more plastic is getting accumulated as one shows the mechanism behind the Great Pacific Garbage Patch (GPGP), the largest of five reported plastic accumulation zones in the world's oceans [11].

It has been estimated that the GPGP covers 1.6 million square kilometers. The mass was revealed to be significantly greater than the first assumptions. The weight is approx. 80,000 tons, which is from 4 to 16 times more plastic than previously reported [12]. Based on coastal clean-up data, fishing, aquaculture and shipping are responsible for 28.1% of the plastic in the ocean. However, from the observation of components of GPGP and other plastic accumulation places, it is estimated that the impact of these industries is significantly higher [13].

The type of floating plastic can be differentiated depending on the material or size. The most commonly found plastics include polyethylene (PE) or polypropylene (PP). Other systems of classification divide GPGP components by size or general categories. The following four size categories were established: microplastic (0.05–0.5 cm), mesoplastic (0.5–5 cm), macroplastic (5–50 cm) and megaplastic (>50 cm). 92% of the mass is made of debris larger than 5 mm. Out of this, at least 46% is comprised of fishing nets [12]. Figure 1 shows photographs of abandoned fishing nets on a beach in Norway.

Plastic migration is one of the causes of the huge GPGP. Available barcode system tracing for the plastic shows that some elements of the debris can be found 10 years later, and 10,000 km away from its origin [14]. A good example of this phenomenon is plastic debris found on beaches in Brazil, where at least 21.4% of the plastic came from Europe [15]. Thanks to satellite buoys, it was possible to track the movement of plastic waste in the marine environment. It was observed that plastic nets, which enter the atolls of the Hawaiian Islands from the northeast, tend to move southwest at a slow pace of 0.35 km per day. Eventually, those fishing nets remained stationary on reefs. The longer they stay, the greater the hazard they pose to the closest habitat. Nets moving with the winds will be moving towards the center of the atolls. Thus, remaining stationary for years and causing environmental issues by passively catching and entangling fauna and flora [16].



Figure 1. Parts of abandoned fishing nets found on a beach in southern Norway (Hessness, August 2022).

2. Ghost Fishing

2.1. What Is Ghost Fishing?

Ghost nets are fishing nets that have been discarded or lost in the ocean by fishing vessels [11]. Issues directly connected with that are bycatch and ghost fishing. Bycatch is observed while fishing. Other species of animals are entangled and caught in the net. This phenomenon can occur during a regular fishing procedure when any other marine species gets involved, except for the fishing species we intended to catch. Bycatch can be minimized by using suitable material, which does not absorb water and, as a consequence, does not change the mesh size. Ghost fishing is a completely passive action when ALDFG is floating and independently continues to catch fish or entangle around body parts of the water animals. This phenomenon seems to be directly connected to the quality of the fishing gear. The use of low-quality fishing gear often results in frequent losses when entangled with obstructions or in rough weather [17].

The problem of losing fishing gear consists of several aspects. Gear is considered abandoned when it is not possible for a fisher to retrieve it. That can happen when the gear is snagged on marine obstructions. Snagging fishing gear, including all types of fishing nets, is identified as a major cause of loss in many fisheries [18]. Additionally, during the fishing operation, it is possible to lose control over the gear and not be able to locate it. This situation can occur when tides or wave action carry the gear from the deployment location. Considerable gear loss can also be caused by interactions with other active fishing gear [19]. Other identified causes are long soak times, fishing in deep habitats, and deploying more gear than can be hauled in regularly [18]. An additional issue resulting in ALDFG is illegal, unreported and unregulated fishing; however, the exact connection is difficult to quantify [20].

It has been estimated that from 500,000 to 1 million tons of fishing gear are likely to enter the ocean and become fishing gear every year [19]. Additional attempts to qualify the problem revealed results with both local and global influence. In South Korea, 11,436 tons of traps and 38,535 tons of gillnets are abandoned every year [21]. What is more? Over 70 km of gillnets were lost in Canada's Greenland Halibut fishery in five years [22]. All those studies were conducted to indicate the significant problem of ghost gear. ALDFG that remains in the water for a sufficient period of time will eventually accumulate sessile organisms in a process called 'bio fouling'. It is suspected that this is the reason why the

net becomes more visible to animals and ghost fishing efficiency decreases with time [23]. Monofilament nets have higher catch rates than multifilament nets. It is because the multifilament net is more visible in the water. Multifilament nets are made of materials buoyant in seawater. However, with time, it loses its properties and sinks down slowly. It has been suggested that stormy weather can accelerate the degradation and biofouling of fishing nets [24]. When the net loses the ghost catch, it can become buoyant again and rise back to the surface, starting the ghost fishing cycle again.

The topic of ghost fishing is relatively new and needs to be researched more, especially on its effects on population levels and available solutions or preventing actions. It has been suggested that ghost fishing nets should be treated separately from other components of marine plastic debris, as it requires a different managerial approach compared to debris originating from, for example, tourism [25].

The performance of a fishing net is highly dependent on the material. Among the most commonly used materials, polyamide (PA) tends to have the highest tensile properties compared to polypropylene or polyethylene. Based on the properties of PA, it was concluded that this material is more suitable for fishing to prevent ghost fishing. Nevertheless, it is possible to change the performance of fishing gear slightly by increasing the yarn diameter or the mesh size. Choosing proper parameters results in higher breaking load, tensile strength, and increases the drag coefficient as well as bending stiffness and breaking strength [26].

Studies on the degradation of nylon 6 showed surprising abilities for water absorption. What is more, the observed behavior after reaching the glass transition temperature suggests the use of this material for other specific applications. Once PA is at or above the glass transition temperature, it will tend to creep upon application of load [27]. That means, after only a few catches and not being used for a long time, the nylon fishing net is going to start losing its properties. As a result, being unable to catch the required number of fish.

2.2. Degradation of Plastic in Marine Environment

In 2016, NOfir reported on the effectiveness of the EUfir system related to ALDFG collection and recycling. The used methodology was called Life Cycle Assessment (LCA) and provided a systematic evaluation of the environmental aspect of the product through all stages of its life cycle. Results obtained in this method are reliable and helpful for achieving a life cycle economy. In this case, LCA was used to calculate the real environmental impact of a great system, from the availability of abandoned fishing equipment to the production of secondary materials after recycling operations. The most noticeable environmental effects of recycling were a decrease in the consumption of non-renewable resources and a decrease in carbon footprint (a decrease in carbon dioxide emissions). What is important to notice is that the most commonly found fishing equipment is made of nylon 6 (approx. 76%) [28].

Ropes and nets are exposed to the influence of oxygen, salt water, ultraviolet radiation and mechanical stress. Fishermen should ensure and care for the strength, elasticity, foldability and density of the material as well as the degradation rate. It has been determined that in the marine environment, the greatest impact on fiber degradation is due to the exposure to sunlight, the most abrasive condition that will degrade the fishing net. The marine environment reveals PA twines' weak resistance to sunlight for long periods at a high temperature. Additionally, nylon 6 fishing nets appear to absorb water and swell after some time [26].

The result of the effect of solar radiation on PA netting twines under ambient conditions revealed a decrease in breaking strength over time. Samples were exposed to direct solar radiation for 780 h, which caused significant changes in their properties. The degradation rate of untreated twines was three times higher than the treated ones. This leads to the conclusion that the exposure of the fishing nets to sunlight should be avoided. Synthetic nets do not need to be dried out as they do not rot and can be stored even when wet. Preventing fishing nets from exposure to sunlight extends the half-life of the net, reduces the capital cost of fishing and reduces the time spent on net maintenance and repair [29].

One of the biggest threats from abandoned fishing gear is the degradation of the material it is made of. During that process, plastic may decompose into dangerous chemical components. The degradation of large plastics is the direct source of microplastics. By observing the fragmentation of PP, PE and PA exposed to benthic conditions at 10 m depth over 12 months and by monitoring their weight, it was possible to estimate the behavior of abandoned plastic in a deep marine environment. Results revealed the presence of microplastic fibers and particles even though the photodegradation was reduced with time. This indicated that an alarming volume of microplastic is produced from the rope debris alone [30].

Microplastics generated from the degradation of macroplastics are called 'secondary microplastics'. Most of the microplastic present in the ocean has its source from land, but there is still a significant influence of marine activities on the amount. Marine-based sources include ALDFG, which releases microplastics during degradation in the water but also on beaches. Additionally, abrasion of aquaculture gear made of plastic and ships covered with synthetic paint releases plastic particles. As mentioned before, the primary causes of degradation are physical aberration and exposure to UV light. It is important to notice that big plastic particles release microplastic long before they themselves become small particles [31].

2.3. Bio-Based and Biodegradable Fishing Gear

Creating bio-fishing gear is one of the ideas for decreasing the amount of plastic waste in the ocean. Even though it has been marked as the solution, in some cases it is not beneficial for the environment and can cause similar harm to the environment as regular fishing gear.

Bioplastic production increased from 0.7 million tons in 2010 to 2.11 million tons in 9 years. More than 45% of production took place in Asia (European Bioplastics 2019). Nevertheless, in 2018, only around 0.6% of total plastic production was bioplastic. Increased demand for bioplastics is expected for the continued growth of this field. The most popular biodegradable bio-based plastics available on the market are the following: polylactic acid (PLA), polyhydroxyalkanoate (PHA) and polybutylene succinate (PBS)—the starch-based polymer. They are used as a substitution for polypropylene (PP), polyester (PET) and polystyrene (PS) [32].

To manufacture biodegradable nets, the following special material blend was synthesized: 82% of PBS mixed with 18% of polybutylene adipate-co-terephthalate (PBAT). The mechanical properties of the blend were compared to the properties of the nylon net. The nylon fishing net exhibited greater breaking strength and elongation when dry and better flexibility when wet—the biodegradable net appeared to be approx. 1,5-fold stiffer. Based on these results, it could be concluded that the bio-fishing net is going to have a lower catch efficiency than the nylon one. Nevertheless, a comparison revealed similar catch rates for yellow croakers. Degradation of the line started after two years, which made the net easy to be destroyed by potentially entangled organisms. The results of that experiment are promising and serve as a solution to the problem of ghost fishing [21].

However, the term bioplastic does not always mean that the material is bio-based or biodegradable. The meaning of the term is that we can find plant-based plastics that are either biodegradable or non-biodegradable, or biodegradable fossil-based plastics [33]. The chemical and mechanical properties of materials highly differ. At the same time, different environments (soil or ocean) greatly influence the biodegradability of bioplastics [34]. Data collected during the last ten years shows that some problems connected with the influence on the environment are the same for bio as well as conventional plastic. Plant-based polymers are not necessarily biodegradable, can contain toxic additives and can degrade and persist as microplastics [2].

One of the most crucial disadvantages of bioplastic is the necessity of designing new recycling lines because it contaminates the recycling process of conventional plastic. Mostly, the sorting of plastic is based on visual examination, which does not distinguish bioplastics from non-bioplastics [35]. For example, PET and PLA (bio-based) plastic bottles look nearly identical, which makes it impossible to sort them based on their appearance. Mixing these two materials during recycling would cause problems for reprocessing because these materials have different melting points [36].

Discarded biodegradable plastic, including biodegradable plastic bags, poses the risk to aquatic life and the environment as those of non-biodegradable plastic. It has been found that they have a similar adverse impact on the infaunal abundance and biogeochemical processes. Based on a comparison of the specific examples of bio-HDPE and conventional HDPE, biodegradable plastic poses the same risk to biodiversity and the ecosystem. Both of them obstruct oxygen and light, decreasing the abundance of invertebrates and decreasing the flux of inorganic nutrients from the sediment [37].

There are still debates concerning the full environmental footprint of bioplastics. Most of the currently available analysis has been limited to carbon dioxide emissions [38]. However, there has been a standard ASTM D 6691 test method, which allows for the determination of the degradation of virgin and biodegradable plastics by aerobic mineralization. To check the behavior of the materials as future fishing materials, the marine environment was simulated in a laboratory. Out of the examined materials, the highest mineralization rate, which indicates degradation and biodegradation in the case of biodegradable plastics, was the highest for thermoplastic strath and plastic waste polymers. Thermoplastic strath showed a mineralization rate of 49.7% after 82 days and achieved 85% degradation after three months. That presents a much higher degradation rate than virgin polymers [39]. Moreover, the biodegradable fishing nets exposed to seawater show degradation after two years, resulting in abrasive changes in the surface [40].

3. The Wide-Ranging Impact of Marine Plastic

3.1. Impact of Marine Plastic on Mammals, Birds and Reptiles

Plastic has been proven to impose detrimental effects on at least 267 species around the world. This includes the following: 86% of sea turtle species, 44% of seabird species and 43% of all mammalian species. Animals are mostly harmed through ingestion (reducing stomach capacity, hindering growth, internal injuries, intestinal blockage), entanglement and subsequent strangulation [41]. Moreover, 340 original publications reported encounters between marine debris and marine animals [42]. At least 17% of those affected by entanglement and ingestion were listed as threatened or near threatened [43].

The number of species proven to be negatively affected by derelict plastic debris has doubled since 1997. Ghost gear is one of the most deadly forms of marine plastic debris [44]. It tends to continue to catch animals as long as it retains proper integrity [45]. This usually occurs during the first year after the loss of ghost gear, but there are observed types of fishing nets continuing to capture animals even decades after being lost [46]. Even though most fishing gear is designed to capture animals in a selective way, it is known by now that when lost, fishing gear can capture animals indiscriminately. It has been documented that in the Salish Sea, more than 260 species have been observed to get entangled and killed by lost salmon gillnets. It has also been estimated that the 4500 nets removed from 2002 to 2009 might have killed more than 2.5 million marine vertebrates, 800,000 fish and 20,000 seabirds [47]. Over 5400 animals from 40 different species of marine mammals, reptiles and elasmobranchs were entangled in ghost fishing nets [25].

Out of all marine mammals, seals and sea lions appeared to be the most endangered species by entanglement. In Australia, it has been estimated that 1500 sea lions die from entanglement every year [48]. In the Sea of Okhotsk, the most common victims of entanglement were young males, as a consequence of their natural curiosity and playful behavior. Additionally, the rotation of the body is a natural panic reaction that causes more entanglement for long periods. Most of the plastic debris found on sea lions was associated

with nearby fishing [49]. There is evidence that even the relatively small entanglement rate of 0.4% of the northern fur seals is serious enough to affect the whole population. This is due to the disproportionate effect on individuals of fertile age [50].

Marine plastic in the form of net, rope, monofilament line and packaging bands can cause entanglement in a wide range of pinniped species. There is a noticeable potential for an acute impact on individuals by starvation and highly restrictive entanglement. Some animals live with chronic deep wounds for months or even years. Chronic wounds may cause a deep infection, leading to the premature death of an individual. The result of marine debris entanglement is the first and foremost suffering of animals through wounding, amputation or ingestion. This often goes hidden and unreported. Fur seals, monk seals, California sea lions, grey seals and common seals are the most likely species to be affected by entanglement [51]. It has been found that over the last two decades, entanglement records of seabirds have increased from 16% to 25%.

Lost fishing gear also damages important nearshore habitats, including seagrass beds, coral reefs and mangroves [52]. Lost fishing gear break corals, damage vegetation, build up sediments and impedes access to specific habitats [53]. It is considered likely that plastic on the seabed alters the dynamics of the entire ecosystem. Upon covering the seafloor, plastic sheets inhibit gas exchange, leading to low oxygen levels and the formation of artificial hard grounds, creating problems of burying creatures [54]. However, some organisms are able to adjust themselves to these conditions. Floating plastic debris was used by a variety of microorganisms as a newly created habitat [55]. Plastic debris also attracts fish or sea turtles to aggregate below its surface and follow the drifting material [56]. Damage to marine and coastal ecosystems [57] is challenging to calculate, but it has been proposed that a 1% decline in annual ecosystem services could equal a loss of USD 500 billion in global ecosystem benefits annually [58].

Plastic microparticles in the marine environment are being absorbed by small organisms at the base of the food chain. They are subsequently transported further up the food chain as the prey is eaten by the predator. Higher and higher concentrations are reached all the way to the top predator species. This process is called bioaccumulation and has an effect on human lives upon the consumption of fish and other seafood. Chemicals from oceanic plastics have been detected in human bodies as well [59].

On average, a human body absorbs approx. 52,000 particles of microplastic by ingestion per year. It is under investigation exactly where in the body it tends to accumulate the most and what kind of negative effect it would have on human health. Depending on the known impact of plastic on human beings, it is supposed that it may contribute to neurodevelopmental disorders, metabolic, respiratory and cardiovascular diseases as well as decreased antibody response to vaccines [60].

3.2. Impact of Lost Fishing Gear on Fisheries

Macroplastics have the potential to reduce the efficiency and productivity of commercial fisheries. The most important impact occurs through ghost fishing by ALDFG [5]. Ghost nets may get caught up and damage the machinery of the fishing boats [61]. Fishing operations near the coastline may have livestock as the nets are being picked up by the animals upon reaching shore.

According to experiments on abandoned and lost crab traps, an estimated 12,193 traps are lost annually in the Washington waters of the Salish Sea. Lost traps still show some catch rate, which results in animals being caught but never picked up. The annual Dungeness crab loss was estimated to be 4.5% of the value of harvest, translating into a value of USD 744,296. Unfortunately, the value of saved crabs is lower than the cost of removal. Nevertheless, the best solution could be to modify the trap design, which might reduce the mortality rate and negative impact on the abundance of crabs [62].

However, studies on the removal of derelict blue crab pots in the Chesapeake Bay showed more promising results. This may encourage fishers to organize an additional removal. Removing 34,408 derelict pots led to significant gains in gear efficiency and an

additional 27% increase in income (USD 21.3 million). Global analysis shows that removing less than 10% of derelict pots and traps could result in a recovery of USD 831 million. Removing ALDFG will not only save marine biota but also appear to be profitable and sustainable for governments and communities whose livelihoods depend on income from the ocean [63].

In 2015 costs induced by derelict fishing gear on fisheries and aquaculture have been estimated at USD 1.47 billion. On transport and shipbuilding at USD 2.95 billion, which gave 13.4% and 27% of annual costs respectively [64]. In the Adriatic and Ionian Seas, the annual loss due to derelict fishing gear for the fishing sector was estimated at USD 21.86 million [65].

3.3. Tourism and Marine Port Operations

Marine plastic debris on beaches and in touristic marine environments (for example, coral reefs) presents a serious visual and aesthetic problem. The presence of litter has a significant negative impact on recreational experiences and overall beach enjoyment [66]. Visitors actively avoid spending time on polluted parts of the coast [67]. This generates lots of opportunities for industries because tourists favor alternative, less polluted locations, reducing income for businesses operated at less visited beaches [2].

The direct cost impact of marine debris on tourism has been estimated in 2015 at USD 6.41 billion, which is 59.2% of the total damage caused by derelict plastic [64]. In the region of the Adriatic Sea, the tourism sector lost an average of USD 6833 per year and harbors needed to spend USD 10,238 on managing marine litter [65]. In Orange County, California, marine litter was reduced by 25%. This saved additional costs for visitors, who no longer needed to travel further in their search for non-polluted beaches [68].

Marine debris can present navigational hazards to ships at sea by entangled propellers, blocked water intakes and collisions with floating objects. Especially when the weather conditions are bad, the entanglement of propellers can significantly reduce stability and maneuverability [69]. Derelict fishing gear causes economic costs here as well, as sometimes changes in routes may be needed to avoid a collision. This may have a significant influence, especially in areas with heavy marine traffic [70].

3.4. Economic Costs

Different economic costs of pollution can be divided into prevention, remediation and damage costs. Prevention costs are the lowest and involve a range of actions organized by civil society organizations, governments and industries to reduce the amount of plastic litter entering the oceans to avoid damage and remediation costs in the future [2]. The annual global economic cost of marine plastic pollution is estimated to be at least USD 6–19 billion globally [71]. The cost of cleaning coasts could be reduced by a proper prevention policy [65]. The total cost of damage in 2015 in the region of the Asia-Pacific Economic Cooperation (APEC) has been estimated at USD 10.8 billion annually [64]. Moreover, the estimated cost of removing marine plastic from a remote atoll in the Seychelles was USD 4.68 million with 18,000 h of labor [72]. In the Republic of Korea, USD 282 million was sent over five years to remove plastic litter [73]. During a period of eight years, Japan spent USD 450 million on ocean plastic removal [74].

These damage costs, including lost opportunity costs and indirect costs, could be significantly reduced by preventing plastic from leaking into the environment. The worsening aesthetic of beaches polluted by waste reduces the number of tourists and income. Not only are fisheries affected (covering costs of damage caused by derelict fishing gear), but also land-based agricultural centers are affected by plastic litter blown onto beaches. Proper municipal clean-up practices are promising opportunities for the prevention of expenditure [2].

4. Recycling and Recommended Practices

4.1. Recycling of Fishing Nets and Effective Actions

The presence of ALDFG in marine environments is due to the following: irresponsible fishing practices, inadequate access to recycling facilities, low return prices for consumable plastic and a high cost of recycling [75]. Mechanical recycling is the simplest process. It involves following the following steps: sorting, cleaning, granulation, drying, melting, extrusion and pelletizing [35]. What is worth mentioning is that developing countries, such as Brazil, China and India, have high plastic recycling rates, between 20% and 60% [76]. In Australia and the United States, plastic recycling is low as follows: 10%–15%, whereas in Western Europe and Japan, recycling rates for plastic are around 25%–30% [76].

Technically, it is possible to separate most plastics into recognizable streams, but not all plastic streams are mechanically processable. It depends on the chemical and mechanical behavior as well as on the thermal properties. Only thermoplastic polymers (for example, polyethylene, polypropylene and polyester) are mechanically recyclable [77]. An alternative to mechanical recycling is chemical recycling, which produces plastic feedstock that can replace virgin plastic [78].

The main challenges for the circular fishing gear design are associated with the following: low utility of current materials, high level of mixing of different materials, lack of legal obligations for recycling from local authorities, lack of support and high cost of alternatives, low use of collection points in harbors and high organic contamination, which reduces the recyclability [79].

The most important practice for addressing the problem effectively is the prevention of gear loss. This is the ultimate goal of any progressive ghost gear program [80]. That is why it is aimed at the temporal separation of different gears, including the prohibition of high-risk types. For example, the Western Central Pacific Fisheries Commission prohibited large-scale driftnets. Additional separation of individual rope and net types is highly beneficial for all processing stages and the requirement to obtain uniform samples for material recycling [80].

Moreover, innovative solutions to end-of-life fishing gear promise to reduce the extent of lost fishing gear. Current actions taken by the European Commission have established a progressive goal of abandoned fishing net collection rate of 50% and a 15% recycling target, both to be met by 2025 [80]. There are many removal programs around the world that are focusing on different strategies of collection or cleaning the oceans. Some of them are highly specific. For example, the Northwest Straits Foundation's program is an initiative focused on the rapid removal of newly lost gillnets [80]. Other recommendations for the prevention of ALDFG are mostly focused on industry and governments. The great interest should be focused on solutions aiming at hot spot plastic areas. Mapping historic, ongoing and possible ALDFG data collection can significantly improve ocean cleaning practices and prevent the accumulation of plastic litter [81].

4.2. Alternative Recycling Options

Among the most important premises for establishing a recycling economy is creating international recycling standards, especially for mechanical recycling, as it is the most well-developed approach in terms of industrial feasibility [82]. One example is the creation of the European Strategy for Plastics in a Circular Economy where the design and production industry meet the needs of reuse, repair and recycling [79].

While eroding, polymeric chains decompose and release various chemical species. One of the most used materials is nylon 6, which was subjected to thermal analysis. The material was decomposed into volatile monomers at a temperature of approx. 400 °C at different heating rates (5, 15, 20 and 30 °C/min) [83]. Results showed that the decomposition of nylon 6 corresponds to a spectrum of caprolactam-based compounds during the most intense stage of decomposition. Pyrolysis of nylon 6 results in the reduction of the material into monomers, indicating the potential for the production of caprolactam. This also implies that waste nets can be converted to monomers via pyrolysis.

Available polymers have limited recyclability potential. Because of carbon-carbon backbone strength, depolymerization to monomers is prevented [84]. Polymers redesigned with ester backbones may be better suited for controlled chemical depolymerization. However, it may also be suitable for biological processing in managed systems, such as individual composting [84]. Even if the polymer satisfies the criteria for use and end-of-life, it is important to prepare a recoverable, sortable and separable product design. An example is the availability of the *APR Design Guide for Plastic Recyclability*, which is currently used in plastic-based packaging.

4.3. Material Mixing Needs

Promising R&D routes for establishing biodegradable fishing net materials often comprise blending mutually compatible biodegradable polymers. A unique R&D route for establishing a marine-degradable fishing net is the incorporation of photocatalyzable ether linkages along the polymer backbone architecture. Other R&D routes for establishing degradable fishing nets may promote biocatalytic degradation by various mechanisms.

However, designing photodegradable or biodegradable materials cannot be the sole solution as the environmental hazard remains for extended durations. Instead, a strong societal need exists for economically attractive “fishing net return schemes” (analogous to plastic bottle deposit schemes) for occupations fishers, providing an economic incentive to minimize abandoned, lost, or discarded fishing gear. The success of such economic return schemes would in the future enable the possibility of more conventional material mixing technologies for upgrading partially biodegraded fish nets. Such material mixing technologies would benefit from new rapid “multidimensional molecular characterization” technology to quantify, on a batch level, the amount of biodegradation experienced on each “homogenous” batch of recovered fishing nets. Such “multidimensional molecular characterization” would incorporate a quantified measure of chemical functional group polydispersity, enabling more accurate predictions of the mechanical properties of recycled polymer mixtures.

5. Alternative Usage of Derelict Fishing Gear

5.1. Research Solutions

Several research institutions have taken the challenge of finding new opportunities for recycled fishing nets and therefore getting them closer to the circular economy. Unfortunately, recycled polyolefin resins from fishing nets seem to have poor properties due to the presence of contamination. The blend of derelict PE nets with different types of virgin resins showed a potential for usage in packaging. Even though the created composites have certain limitations, it was possible to meet the required elongation at break as well as impact strength and environmental stress cracking resistance. With a properly chosen virgin resin, it is possible to use the plastic from fishing nets in packaging [85].

Interesting results were presented with the usage of recycled nylon fibers as tensile reinforcement of cementitious mortars. A significant increase in tensile strength and toughness was observed. Unreinforced material achieved approx. 35% lower tensile strength and up to 13 times lower toughness [86]. Moreover, it was discovered that the fibers of nylon fishing nets helped transfer stress through cracks and distribute stress by transforming a single wide crack into several smaller ones [87].

Obtaining the oil from the waste fishing net as a substitute for diesel fuel has been another, albeit uncommon investigation. This too, achieved some promising results. Oil from waste fishing nets possesses excellent fuel properties, with a calorific value of 44,450 kJ/kg (higher than diesel by 1.48%). Additionally, it works on a diesel engine without requiring any engine modifications. Nevertheless, the brake thermal efficiency decreased. Brake-specific fuel consumption increased, and so did engine emissions [88]. This is still, however, an idea worth further investigation as it may prove useful for retrieving fossil fuels.

Table 1 provides an overview of various market applications of ALDFG.

Table 1. Examples of different market applications for ALDFG.

Type of Recycled Fiber	Market Application	Company
Polyethylene fishing nets mixed with different virgin resins	Packaging	Polymer Technology Laboratory, Spain
Nylon	Tensile reinforcement of cementitious mortars	University of Salerno, Italy
Nylon	Stress distribution in construction cracks	Hokkaido University, Japan
	Substitute for diesel fuel	College of Engineering, India
Nylon	Carpets and clothing	Gabriella, Poland
Mix of derelict fishing nets	Jewelry (New Stone design line)	Orska, Poland
Polypropylene waste	Material called Boomplastic used to make “Circula” bench	Studio Rygalik, Poland
Nylon fishing nets	Material called Econyl used to make spectacle frames	Karun, Chile
Different fishing fibers mixed with wooden fiber	Kelp Chair	Design Milk, Sweden

5.2. Solutions in Product Design

In general, governments and international and local companies are aware of the negative impact of ALDFG on both the environment and the economy. To solve this problem, research on creating a new product by using the waste from fishing nets has already started. Currently, there are already being developed interesting solutions for transforming fishing ropes into nylon yarn for the production of clothes and carpets [89]. One of the many examples of using nylon fibers for clothing production is a Polish company named Gabriella. In 2021 designed tights consisting of 70% of oceanic wastes [90]. It has been proven that it is both possible and profitable to create sustainable and aesthetically pleasing products.

With the common initiative of the foundation MARE and the jewelry design company ORSKA, derelict fishing nets from the Baltic Sea were used for creating a new collection line. Ground fishing fibers were mixed with granules of recycled plastic that had undergone a thermal treatment, which resulted in the material used for creating the New Stone design line [91]. The Stone was created with the help of Tomasz Rygalik, the owner and designer of the Studio Rygalik company. His previous work shows the possibility of designing products out of plastic blends. He has created a material called Boomplastic, which has found its use in the creation of outdoor furniture—creating a garden bench called Circula. Boomplastic is a blend of polypropylene and colorful flakes obtained from polypropylene packages and bottle caps. The transparent matrix came from the grinding of damaged polypropylene bottles and cups [92].

Another brand called Karun started to create its products from plastic waste over 10 years ago. Their material is called Econyl, which is a nylon coming from ghost-fighting nets found in the ocean. Out of this plastic, there has been created spectacle frames, now available around the world [93]. Additionally, in 2022, the design company Design Milk from Sweden presented the innovative project of the 3D printed chair, using recycled fishing nets and wood fiber [94]. The creation of the Kelp Chair [94] prevented fishing nets from ending up in the depths of the Baltic Sea and instead turned them into new material. Promising results from research and usage of these materials create optimism for the further development of this field. The examples shown above indicate that recycling ALDFG and turning it into new material might become an economically profitable field. These new plastic types might be able to reduce the amount of virgin plastic entering the environment as well as limit costs connected to marine plastic debris.

6. Conclusions

Marine litter, and in particular plastic waste, including plastic from abandoned and derelict fishing gear, is a growing environmental concern. The influence of abandoned and derelict fishing gear is enormously threatening to natural marine and coastal habitats and endangered species. As well as being a burden on both the local and global economy. Designing materials, which are increasingly biodegradable, cannot be the sole solution to marine litter because the environmental hazard still remains for long stretches of time. It needs to be combined with a feasible plan for recovery and transformation into products that can compete in the open market. New research and businesses are already presenting alternative recycling paths and utilization of used fishing gear, which may be of benefit both environmentally and economically.

In the context of fishing net recycling, mixing pristine and partially degraded fishing net polymers marginally decreases new plastic production volumes. For re-usage as fishing nets, the mechanical properties of the recycled polymer must meet or exceed the pristine polymer's mechanical properties. In this manner, economically attractive return schemes can be implemented, reducing ecological harm caused by abandoned, lost, or discarded fishing nets.

Author Contributions: Conceptualization, A.K., K.G.P. and S.K.; writing—original draft preparation, A.K.; writing—review and editing, A.K., K.G.P. and S.K.; supervision, K.G.P. and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge Christian Karl and Anna-Maria Persson, both at SINTEF Industry in Oslo, Norway, for insightful conversations.

Conflicts of Interest: The authors declare no conflict of interest.

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