Process Safety and Environmental Protection 182 (2024) 1143–1152

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.journals.elsevier.com/process-safety-and-environmental-protection

Mitigation approach of plastic and microplastic pollution through recycling of fishing nets at the end of life

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ARTICLE INFO

Keywords:
Fishing nets
Recycling
Plastic pollution
Composites

ABSTRACT

Plastic and microplastic pollution in the marine environment is a global issue and lost or discarded fishing nets (FNs) represent a relevant part of the marine litter. This type of waste is very harmful to marine organisms due to ghost fishing and microplastics release. Furthermore, nets are difficult to dispose because they take up a lot of space at landfill sites and are expensive to transport. Therefore, the development of recovery and recycling strategies represents one of the solutions for this problem. In the present work, a multifilament, knotted, twisted waste FN, composed of nylon 6,6, was recycled realizing composite materials in combination with recycled expanded polystyrene (EPS) or poly(acrylonitrile-butadiene-styrene) (ABS) matrices. The composites were realized exploiting a cold mixing approach, mixing the FN, either as a pre-ground short fiber filler or as mats, with the polymers swollen in an organic solvent. Several compositions were explored by these approaches and the composites were characterized by means of thermal, spectroscopic, mechanical and morphological analyses. Finally, a qualitative assessment of the economic impact of fishing net recycling was conducted. Results showed that the proposed recycling approaches allow to realize composite materials with interesting properties, opening new routes for recycling the FNs at the end of life improving the circular economy of plastics and reducing their ecological, ecosystem service and social and economic impacts.

1. Introduction

In the context of environmental issues, plastic and microplastic pollution in the marine environment is one of the most pressing. Plastics are widely used for their properties and versatility, making them suitable materials for countless applications (Friot and Boucher, 2017) and plastic production increased over the years, reaching about 390 million tons per year (Plastics Europe, 2022). Due to improper disposal of plastic waste, a large amount of these materials end up in marine ecosystems (Prata et al., 2019) and the resulting effects are increasingly evident. It was esteemed that 14 million tons (Mt) of plastic end up in the oceans (IUCN, 2021) every year, part of these wastes consists of abandoned or discarded fishing gear (FAO, 2022; GESAMP, 2021; Gilman, 2015; IUCN, 2021; Lively and Good, 2018; UNEP, 2016), such as FNs, longlines and traps. In a study conducted along Cape Milazzo coast (Sicily, Italy), on 793 items, counted analyzing 18:45 h of video recording, the 77.6% was detected to be derelict fishing gear (Consoli et al., 2019). In general fishing gear appears to be among the main sources of marine litter in the Mediterranean Sea (Melli et al., 2017; Tubau et al., 2015). This type of waste is worrying, because is very harmful to marine ecosystems (Wilcox et al., 2015) and difficult to dispose of, because it is a voluminous waste taking up space at landfill sites and is expensive to collect and to transport to waste management sites (Bertelsen and Ottosen, 2022).

The main problems related to the loss of fishing gear are the release of microplastics and ghost fishing. When plastic ends up in the sea, over time, environmental conditions, such as abrasive actions or sunlight exposure, cause them to break up into progressively smaller fragments, leading to the formation of secondary microplastics defined as plastic particles smaller than 5 mm (IUCN, 2021) or as any solid plastics particle insoluble in water with a size ranging between 1 μm and 1000 μm (ISO/TR 21960:2020(en)) since the terminology and the different classification of microplastics are still debated (Federici et al., 2022). These particles appear to be ubiquitous, reaching even remote marine

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https://doi.org/10.1016/j.psep.2023.12.031
Received 14 October 2023; Received in revised form 7 December 2023; Accepted 12 December 2023
Available online 15 December 2023

environments and have a great impact on ecosystems (Taylor et al., 2016). For example, they can be ingested by marine organisms (Wright et al., 2013), blocking digestion and damaging the stomach (Taylor et al., 2016). Moreover, they can be transferred from one trophic level to the next, causing contamination of the food chain (Mercogliano et al., 2020; Santonicola et al., 2021, 2023; Volgare et al., 2022). In 2018, a significant microfibers release from FNs was estimated by simulating marine conditions with Linitest equipment (Montarsolo et al., 2018). The results also showed a variable release, probably attributable to the structure of the nets and to its level of degradation.

Ghost fishing is a phenomenon whereby the derelict fishing gear can continue to catch marine species (Gilman, 2015; Lively and Good, 2018). Among the fishing gears that can be at the origin of this phenomenon, FNs are the most common (Lively and Good, 2018). FNs are typically made up of synthetic fibers: polyethylene (PE), polypropylene (PP), polyester (PES) or nylon (Bertelsen and Ottosen, 2022). The mesh can have different sizes and can also be knotted (single or double knot) or not, made with multifilament or monofilament. Several studies have investigated the impact of ghost nets on marine organisms. The effect of abandoned, lost, and discarded fishing gear on marine turtles was investigated in 2015 in Northern Australia (Wilcox et al., 2015). In this study, the damage of marine turtles due to specific type of nets, associated with particular fisheries, was examined. It was found an increase in the probability of entanglement for marine turtles in nets with larger mesh and smaller twine sizes, as larger nets appeared to attract turtles. In 2010, derelict fishing gear were recovered at sites throughout Puget Sound and the Northwest Straits (Good et al., 2010), and marine organisms captured by gillnets were estimated to be 31,278 invertebrates (76 species), 1036 fishes (22 species), 514 birds (16 species), and 23 mammals (4 species). 56% of invertebrates, 93% of fishes, 100% of birds and mammals were found dead due to derelict fishing gear. The impact of lost fishing gear was studied on corals in the Gulf of Thailand where nets were the most common type of lost gear (Valderrama Ballesteros et al., 2018). Corals underneath gear were found to exhibit the most damage, in particular tissue lost.

In such scenario, lost fishing gear represents a big issue for the marine ecosystems. In light of the fact that fishing operations have increased in recent years (Montarsolo et al., 2018), the development of new strategies for the management of fishing gear at the end of life (EOL) is still a challenge.

The need to reduce plastic pollution from fisheries was received in European directives correlated to circular economy. In fact, the EU Strategy for Plastics in a Circular Economy (European Commission, 2018), the Single-Use Plastic (SUP) Directive (Directive (EU) 2019/904, 2019), the Port Reception Facilities (PRF) Directive, the Extended Producer Responsibility (EPR) schemes, and the MARPOL 73/78 Convention give indications to improve management of EOL fishing gear and marine litter in general. In agreement with these directives, the DG MARE studied the circularity of the fishing gears in Europe (MRAG, 2020), highlighting that the scientific community efforts were focused to evaluate the impacts and potential solutions to Abandoned, Lost, or otherwise Discarded Fishing Gear (ALDFG), while their collection, monitoring, redesign, recycling, and reuse approaches have been overlooked and thus, they need to be addressed to meet the targets (Basurko et al., 2023). In this respect, a first strategy could be thermo-mechanical recycling approach of FNs. Several studies have moved in this direction (Juan et al., 2021; Mondragon et al., 2020), however this method requires a complex pre-treatment of FNs recovered in marine environment, due to the high level of impurities and contamination (Weißbach et al., 2022) that, as for other classes of EOL materials, could negatively affect their recyclability (Castaldo et al., 2019). Mondragon et al. in 2020 (Mondragon et al., 2020), used a twin-screw extruder to process polyamide 6 (PA6) from FNs waste and good results were obtained by comparing the mechanical properties of the resulting materials with that exhibited by commercial PA6, suggesting that their use in marine environment does not strongly affect their mechanical behavior. Juan et al. in 2021 (Juan et al., 2021), investigated the possibility of blending the FNs made by polyethylene (PE) with a virgin High Density Polyethylene (HDPE) by using a twin-screw extruder, but the mechanical properties of the resulting materials decreased with the increase of amount of recycled FNs. In recent years, the opportunity to use the fibers of the nets as reinforcement in matrices of different nature was investigated and several works have been focused on the application of these materials in cement-based matrix (Bertelsen and Ottosen, 2022; Nguyen et al., 2021; Orasutthikul et al., 2017; Park et al., 2021; Srimahachota et al., 2021; Truong et al., 2021). Park et al. investigated the influence of the yarn type of the PE FNs on the realization of composites with cement-based matrix. Three types of FNs with different yarn, straight and twisted yarn, were used to realize composites with different compositions. The results indicated that the mechanical properties of the realized materials were influenced by the volume of the fibers as well as by the yarn type.

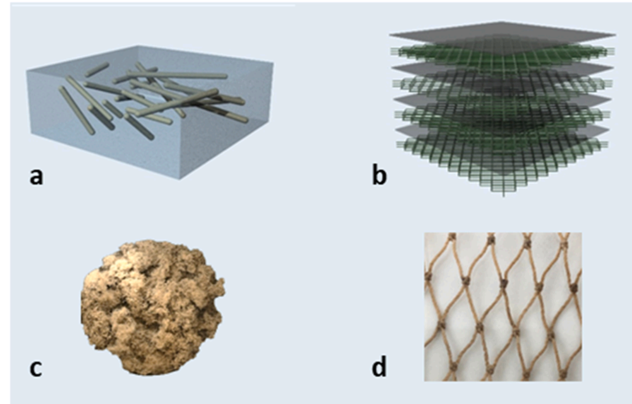

Fig. 1. Recycling FNs in fibrous reinforced composites by: a) grinding approach, b) lamination approach, c) fibrous fraction used in the grinding approach d) FN used in the lamination approach.

In this article, a sustainable, cost-effective technological approach aiming at the recycling of EOL FNs in highly filled composite materials using polystyrene (PS) or poly(acrylonitrile-butadiene-styrene) (ABS) as continuous phase was developed. Two different routes were explored to recycle FNs:

- i) grinding approach: FNs were ground and used as fibrous filler in the realization of fibrous reinforced composites. Materials containing 80, 60 and 50 wt% of fibers were obtained incorporating the filler fraction into a fluidified post-consume expanded polystyrene (EPS) matrix or ABS matrix, by using a cold mixing approach (Cerruti et al., 2014);.

- ii) lamination approach: layers of FNs were used in the realization of continuous fiber reinforced composites by combining the layers of nets with layers of polystyrene. Layers of polystyrene, obtained by casting of fluidified post-consume EPS were applied to net layers by compression molding. Both techniques were efficient and functional for the obtainment of new composites made with post-consume materials. Morphological, thermal, and mechanical analyses were performed and proved the effectiveness of the proposed approach to recycle EOL FNs.

In Fig. 1 schemes of the two approaches are drawn, along with the appearance of a fragment of the net and a ground sample.

2. Materials and methods

2.1. Materials

EPS recovered from packaging boxes and commercial ABS (Terluran GP35, INEOS Styrolution Group GmbH, Frankfurt am Main, Germany) were used as matrices for the realization of composites. FNs at the end of life were multifilament, knotted, twisted nets Fig. 1d), recovered from

Table 1
Composition and code of the realized composites.

Code	Matrix	Fibrous Filler wt%	Net Layer wt%
Grinding Approach			
FNEPS50	EPS	50	
FNEPS60	EPS	60	
FNEPS80	EPS	80	
FNABS50	ABS	50	
FNABS60	ABS	60	
FNABS80	ABS	80	
Laminate Approach			
LFNEPS	EPS		50
LFNABS	ABS		50

the port of Naples – Italy. The chemical composition of the FN was evaluated by using Fourier transformed infrared spectroscopy, FTIR, as described below.

2.2. Preparation of recycled composites

2.2.1. Grinding approach

FN were cut in small pieces and ground using a Retsch mill SM100 (Retsch GmbH, Haan, Germany) with a 4 mm mesh. The obtained fibrous fraction (Fig. 1c) was used as filler to realize fiber reinforced composites.

The fibrous filler was mixed in the matrices using a cold mixing approach at room temperature (Avella et al., 2006). Following this approach, 15 g (12 g, 6 g) of EPS or ABS were dissolved in a proper amount of acetone obtaining a viscous gel. In the case of EPS, the viscous gel forms immediately, while for ABS it is necessary to leave the polymer in acetone for 24 h. After gel formation, different amounts of fibrous filler (50, 60, 80% by weight) were added, mixed at room temperature with a spatula and dried under a fume hood for 24 h and then in oven for two hours at 60 °C under vacuum. Dried samples were pelletized, and pellets were compression-molded using a hydraulic press (Collin P200E, Ebersberg, Germany), at 200 °C for 5 min at 50 bar. Sheets with 3 mm thickness were obtained. The compositions of the realized composites are reported in Table 1.

2.2.2. Laminate approach

Nets were cut into 8 cm × 6 cm pieces. EPS was dissolved in acetone and, after gel formation and solvent removal, the layer of the PS was dried in oven at 60 °C. Then it was compression-molded in thin films

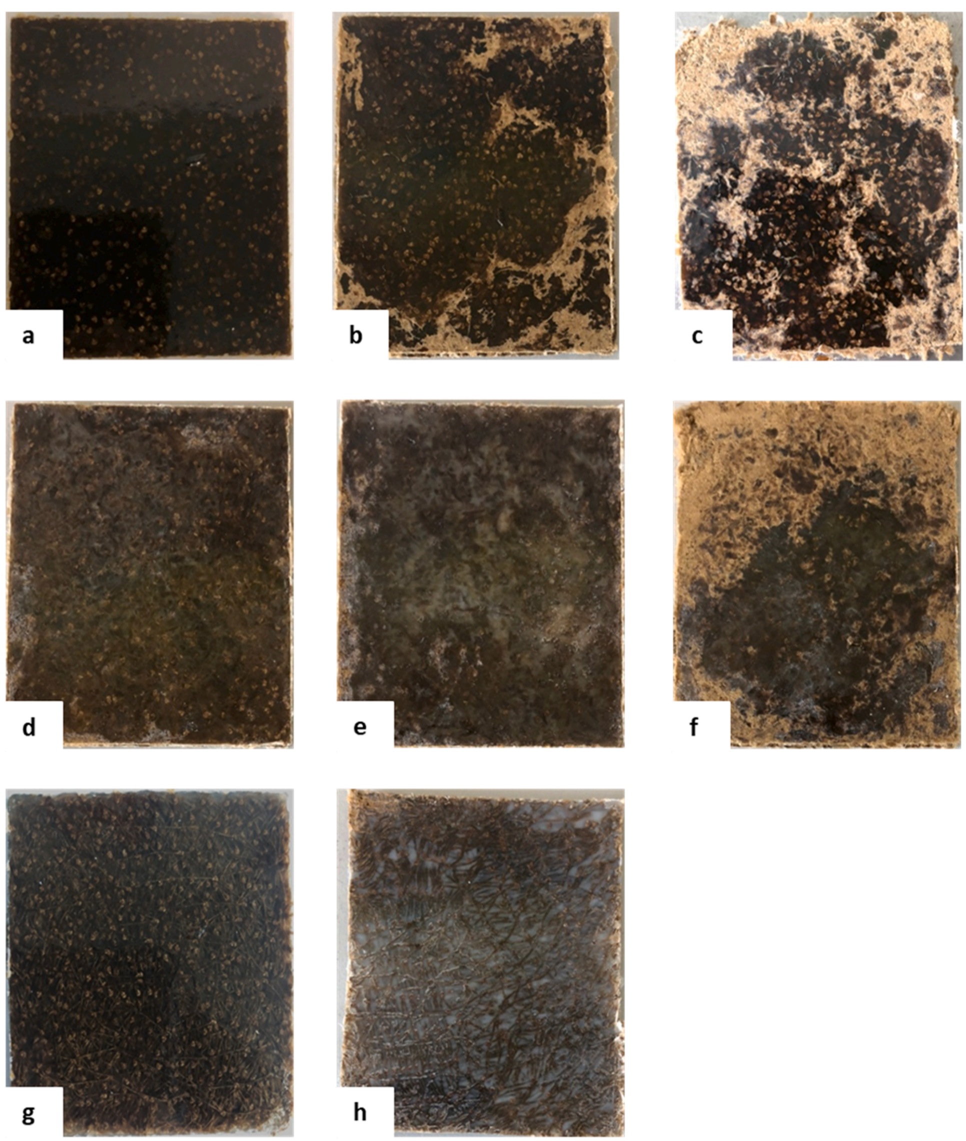

Fig. 2. Samples obtained by grinding approach: **a)** FNEPS50, **b)** FNEPS60, **c)** FNEPS80, **d)** FNABS50, **e)** FNABS60, **f)** FNABS80; and by laminate approach: **g)** LFNEPS, **h)** LFNABS.

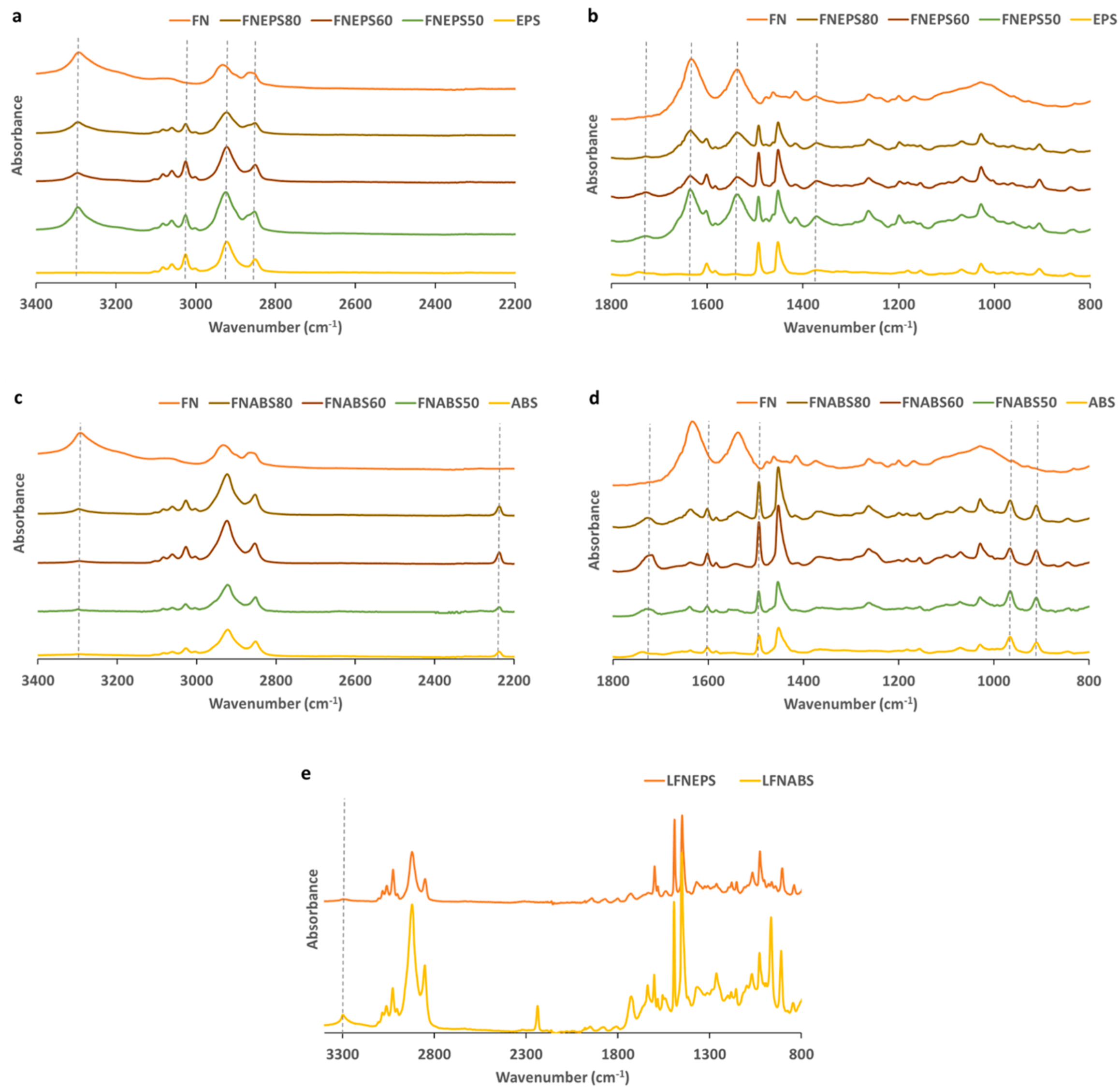

Fig. 3. ATR-FTIR spectra of the composites in different spectral range, obtained by grinding approach: a,b) EPS matrix, c,d) ABS matrix and e) by laminate approach: with EPS and ABS matrix.

with 1 mm thickness at 200 °C, 50 bar for 5 min. Net layers and PS thin films were arranged in alternate layers (9 layers: 5 of FN and 4 of matrix) obtaining a composition with 50% of FN. The samples were compression molded at 200 °C, 50 bar for 5 min to obtain sheets 3 mm thick. The samples with ABS as matrix, were obtained by using the same procedure.

2.3. Analytical techniques

Fourier Transformed Infrared (FTIR) spectra of the net and of the prepared samples were recorded at room temperature by means of a Perkin Elmer Spectrum 100 FTIR spectrometer (PerkinElmer Inc., Waltham, MA, USA), equipped with an attenuated total reflectance accessory (ATR), in the range 4000 – 650 cm^{-1}. All spectra were recorded at a resolution of 4 cm^{-1}, 16 scans were averaged for each sample.

Thermal properties were determined using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). DSC measurements were performed using a TA-Q2000 differential scanning calorimeter equipped with a RCS-90 cooling unit (TA Instruments, New Castle, DE,USA). The instrument was calibrated in temperature and energy with pure indium. About 5 mg of the samples were sealed into a Tzero® aluminum pan. The measurements were carried out heating samples from 25 to 300 °C at 10 °C/min. High-purity nitrogen gas was fluxed at 20 mL/min during all measurements.

TGA measurements were carried out using a Perkin Elmer Pyris 1 analyzer. About 5 mg of each sample were placed in a platinum open pan and heated from room temperature to 800 °C at 10 °C/min in a nitrogen atmosphere.

Morphological analysis was performed on the fractured surface of the samples using a FEI Quanta 200 Field-Emission Gun (FEG) Scanning Electron Microscope (SEM) (FEI, Hillsboro, OR, USA) working in high vacuum mode with an acceleration voltage ranging from 10 to 30 kV and using a secondary electron detector on the fractured surface of the samples. Before the analysis, samples were mounted on aluminum stubs and coated with Au/Pd alloy by means of an Emitech K575X sputtering device.

Three-point flexural tests were performed on an Instron 4505 machine (ITW group, Glenview, IL, USA) at a crosshead speed of 2 mm/min and with a span length of 48 mm to evaluate flexural modulus and flexural strength. The specimen cross-section was 24 mm^2; for each composition, 4 specimens were tested, and the average and standard deviation values of flexural modulus and strength were calculated. Fracture tests were performed by means of a CEAST Resil Impactor

Charpy pendulum (ITW group, Glenview, IL, USA) equipped with a DAS 4000 Acquisition System, using an impact energy of 3.6 J, an impact speed of 1 m/s and a span length of 48 mm. Samples (8 mm wide, 3.5 mm thick, and 60 mm long) with a notch depth-to-width ratio of 0.3, were fractured at room temperature. For each composition, three specimens were fractured, and the average and standard deviation values of resilience were calculated.

3. Results and discussion

3.1. Preparation of recycled composites

The cold mixing approach used in this work, exploits the ability of an organic solvent (acetone) to promote a substantial swelling of EPS and ABS, resulting in a gel-like, low viscosity phase. This fluidified phase is able to efficiently incorporate high amounts of filler, obtaining a good dispersion even in the absence of surface modifiers or compatibilizing agents. Furthermore, the low toxicity and low boiling point of the acetone and its water solubility facilitate its complete recovery, thereby minimizing concerns associated with the use of organic solvents in industrial processes. The used FNs were made of nylon 6,6, as confirmed by FTIR-ATR spectroscopy. As can be seen in Fig. 2, using the grinding approach homogeneous composite sheets were obtained for compositions up to 60% of fibrous filler in the case of ABS (Fig. 2d-f) and up to 50% in the case of EPS (Figures2a-c), while, in the case of lamination approach the homogenous composite sheets were obtained using both EPS or ABS as matrix (Fig. 2g and h).

3.2. Spectroscopic analysis

FTIR-ATR spectra of neat materials and composites are reported in the Fig. 3. EPS based composites, see Fig. 3a, show the typical absorption bands of PS centered at 3060 to 3026 cm^{-1} due to aromatic C–H stretching vibrations; at 2923 and 2848 cm^{-1} due to C-H asymmetric and symmetric stretching vibrations of methylene groups; at 1600, 1492 and 1452 cm^{-1} due to carbon–carbon stretching vibrations in the aromatic ring; at 1069 and 1028 cm^{-1} due to C–H bending of the phenyl ring (Olmos et al., 2014). The main absorption peaks of PS are also present in the FTIR spectra of the composites. The addition of FNs induces the appearance of an absorption band centered at 3297 cm^{-1}, this band was detected in composites with 80%, 60% and 50% of ground FN and associated to the stretching of N-H from amide groups of nylon fibers. The characteristic amide I (C=O stretching), amide II (C-N stretching and N-H bending), and amide III (C-N stretching) absorption of Nylon 6,6 were also observed in the composites at 1632, 1536, and 1368 cm^{-1} (Lee et al., 2020). All samples exhibit a band at 1727 cm^{-1} due to the C=O stretching vibration which may have formed by oxidation during the compression molding.

ABS composites show an adsorption band at 2237 cm^{-1}, attributed to the stretching of nitrile groups of the polyacrylonitrile segment. Furthermore, the samples present peaks at 1638, 967 and 911 cm^{-1} due to the C=C stretching of butadiene and the vibration of CH bonds. A styrene ring stretch band at 1490–1602 cm^{-1} is also visible (Desrousseaux et al., 2015). As EPS composites, also the spectra of ABS composites exhibit bands at 3297 cm^{-1}, 1632, 1536, and 1368 cm^{-1} associated to the amide groups of nylon fibers. In addition, the band at 1726 cm^{-1} corresponds to the vibration of carbonyl groups generated by oxidation (probably of polybutadiene segments) during the compression molding. In the case of laminates, essentially the main absorption peaks of PS and ABS are present in the spectra of the relative laminates and only the band at 3297 cm^{-1} associated to the polyamide phase was detectable. The layered structure of these materials, in fact, presents a "skin" layer constituted by the EPS or ABS matrices, masking the presence of FN during ATR analysis.

Table 2
Results of DSC Analysis: Melting Temperature (T_m) and Glass transition Temperature (T_g).

Composite Code	T_m (°C)	T_g (°C)
Grinding Approach		
FNEPS50	217	106
FNEPS60	217	106
FNEPS80	217	ND
FNABS50	216	105
FNABS60	217	107
FNABS80	216	ND
Laminate Approach		
LFNEPS	216	103
LFNABS	216	107

3.3. Thermal analysis

In Table 2 and Fig. 4, results of DSC analysis are reported. The DSC thermograms in Fig. 4 reported the thermal behavior of the neat EPS and FNEPS composites (50–80 wt%) during the first heating cycles. Neat EPS and FNEPS composites contain FN loadings of 50–60 wt%, exhibit a glass transition temperature (T_g) at 106 °C, associated to the EPS phase, and a melting temperature at 220 °C, compatible with the melting of Nylon 6,6 (Rieger, 1996). For the composition containing 80% of FN the glass transition temperature was not detectable, due to the low amount of EPS in this sample while the composite melting peak of Nylon 6,6 was clearly observable (Zhang et al., 2003). A similar thermal behavior was detected in FNABS samples. FNABS composites containing 50% and 60% of FN presents the glass transition temperature of the ABS phase at temperature of about 105 °C as well as the melting of Nylon at 216 °C (Yang et al., 2004); the FNABS80 shows only a strong melting peak while the T_g was not detectable. Laminate samples with both EPS and ABS matrices presented the same signals, a glass transition temperature typical of the matrix phases and the melting peak related to FN.

TGA analysis allowed to study the thermal stability of the composites. All the samples show a consistent weight loss occurring in a single step between 400 and 500 °C. The temperature of the initial weight loss calculated at the onset of degradation (T_{onset}) and the temperature at the maximum rate of degradation (T_d) are summarized in Table 3. The thermal stability of the composite is not affected by the amount of fibrous fraction in the composites, in fact, all the samples exhibit a similar T_{onset} and T_d.

The same effect was obtained with laminate approach indicating that the different distribution of FN phase in the matrices does not affect the thermal stability of the composites.

3.4. Flexural and impact tests

Flexural and impact tests results are summarized in Table 4 and shown in Fig. 5.

In the samples with EPS matrix, the increase of the amount of FN fibrous fraction led to a decrease in the flexural modulus (Fig. 5a), and a decrease of the stress at break. This is expected to some extent, as the PS matrix has a high flexural modulus (around 3500 MPa) (Wypych, 2012) and the addition of the FN fibrous fraction with a comparable or lower elastic modulus will not have positive affects on the composite stiffness. Moreover, the observed decrease of the flexural modulus could be influenced by the non-homogeneous distribution of the phases at high FN content, as shown in Fig. 1. On the contrary, the modulus values of ABS-matrix composites slightly increase with increasing the fibrous fraction (Fig. 5a). In this last case, the fibrous filler is stiffer than neat ABS, contributing to increases the composites stiffness. This effect is larger in laminate composites based on ABS, where the presence of FN in the form of intact, long fibers induce a stronger increase in the flexural Modulus.

The different preparation approaches used for the recycling of FNs

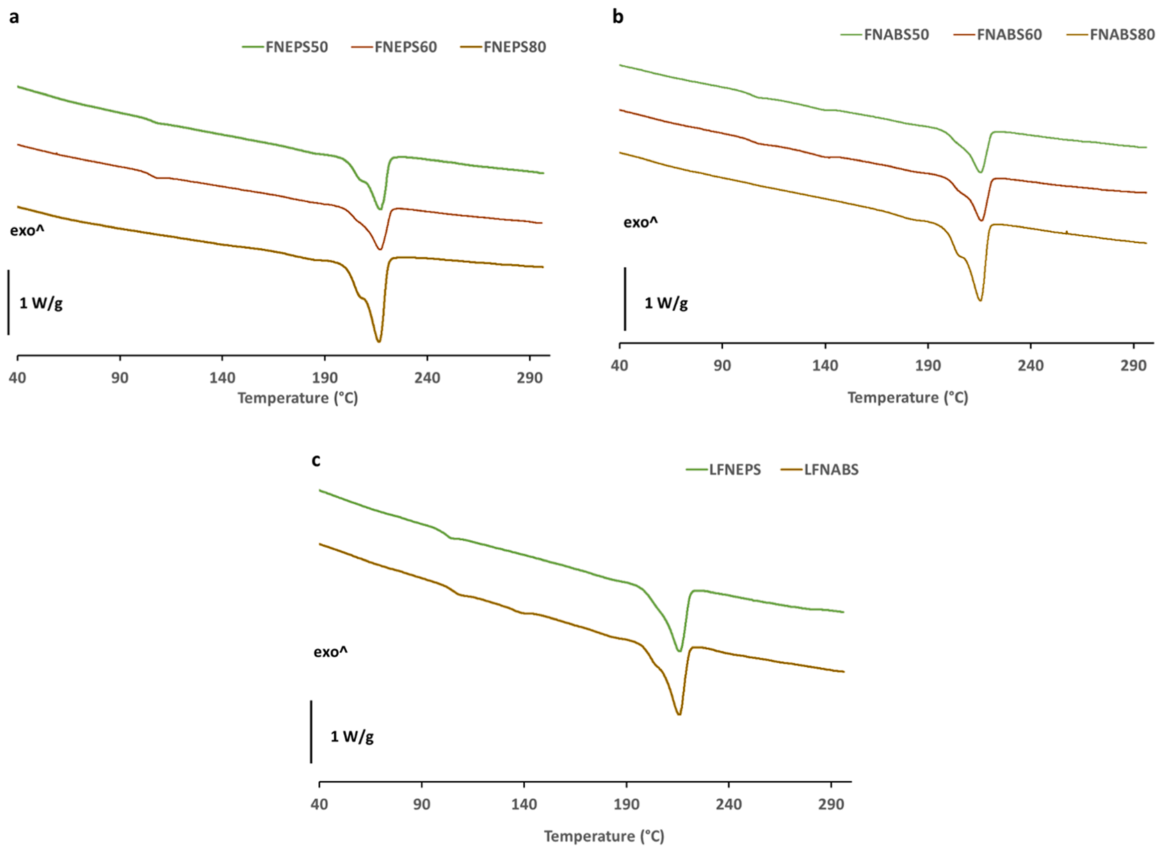

Fig. 4. DSC thermograms; a) EPS based composites obtained by grinding approach, b) ABS based composites, c) EPS and ABS based composites obtained by laminate approach.

Table 3
Results of TGA Analysis: Onset Temperature (T_{onset}) and temperature at the maximum rate of degradation (T_d).

Composite Code	T_{onset} (°C)	T_d (°C)
Grinding Approach		
FNEPS50	396	439
FNEPS60	395	432
FNEPS80	395	436
FNABS50	391	439
FNABS60	404	446
FNABS80	402	443
Laminate Approach		
LFNEPS	393	420
LFNABS	402	434

Table 4
Mean and standard deviation of the results of the flexural and impact tests obtained on four and three specimens respectively.

Sample	Elastic modulus (MPa)	Stress at break (MPa)	Resilience (KJ/m^2)*
Grinding Approach			
FNEPS50	2920 ± 70	38 ± 2	4 ± 1
FNEPS60	2700 ± 100	38 ± 2	7 ± 1
FNEPS80	1900 ± 200	31 ± 2	3.8 ± 0.4
FNABS50	2290 ± 80	41 ± 5	4 ± 1
FNABS60	2360 ± 60	36 ± 4	6 ± 1
FNABS80	2400 ± 400	37 ± 7	6.2 ± 0.4
Laminate Approach			
LFNEPS	2400 ± 200	34 ± 3	15 ± 3
LFNABS	2540 ± 90	50 ± 4	15 ± 6

* from impact test

influence not only the modulus values but also their flexural strength. In fact, for the samples obtained with the grinding approach using EPS as matrix, the stress at break decreases with increasing the fibrous fraction while in the case of ABS matrix it remains almost constant with increasing FN fraction, in the laminate approach the samples containing ABS present the highest value of strain at break (Fig. 5b). As the stress at break parameter in composites is highly sensitive to the adhesion between the phases, the better performances of ABS based materials can be attributed to a higher affinity between ABS and Nylon, due to the presence of polar nitrile groups, with respect to EPS which is non-polar. This aspect has been further discussed in the Fracture surface analysis section.

Finally, the effect of the FNs on the impact strength of the composites was evaluated in terms of Charpy impact resilience values. As observed in Fig. 5c, resilience was affected by the approach used to realize composites. In fact, laminates, both with ABS and with EPS, present values of resilience up to two-three times higher than the other samples. Several factors can influence the energy dissipated by the fracture propagation: matrix fracture energy, fiber fracture energy, de-bonding and pull-out phenomena (Kardos, 1985). The impact strength of composites with short fibers, as in the case of samples prepared by grinding approach, is worse due to inhomogeneity of fiber dispersion and, in the case of EPS based samples, poor interfacial adhesion (as discussed in next section). In the composites prepared with laminate approach, fibers are very long compared to other samples. In this case, the improvement of the impact strength mainly depends on the presence of a continuous phase consisting in the FN mats.

3.5. Fracture surfaces analysis

To evaluate the morphology of the samples, fracture surfaces

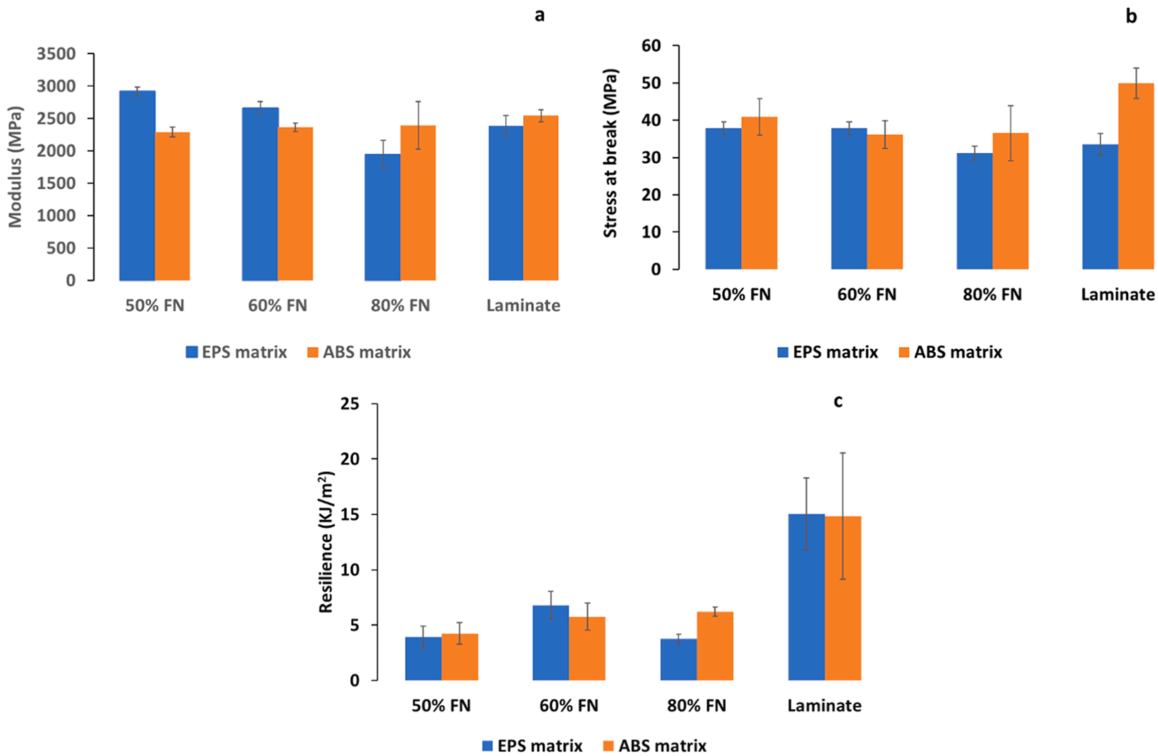

Fig. 5. Comparison of the mechanical properties between the different compositions; a) Modulus obtained from flexural test; b) Stress at break obtained from flexural test; c) Resilience obtained from impact test.

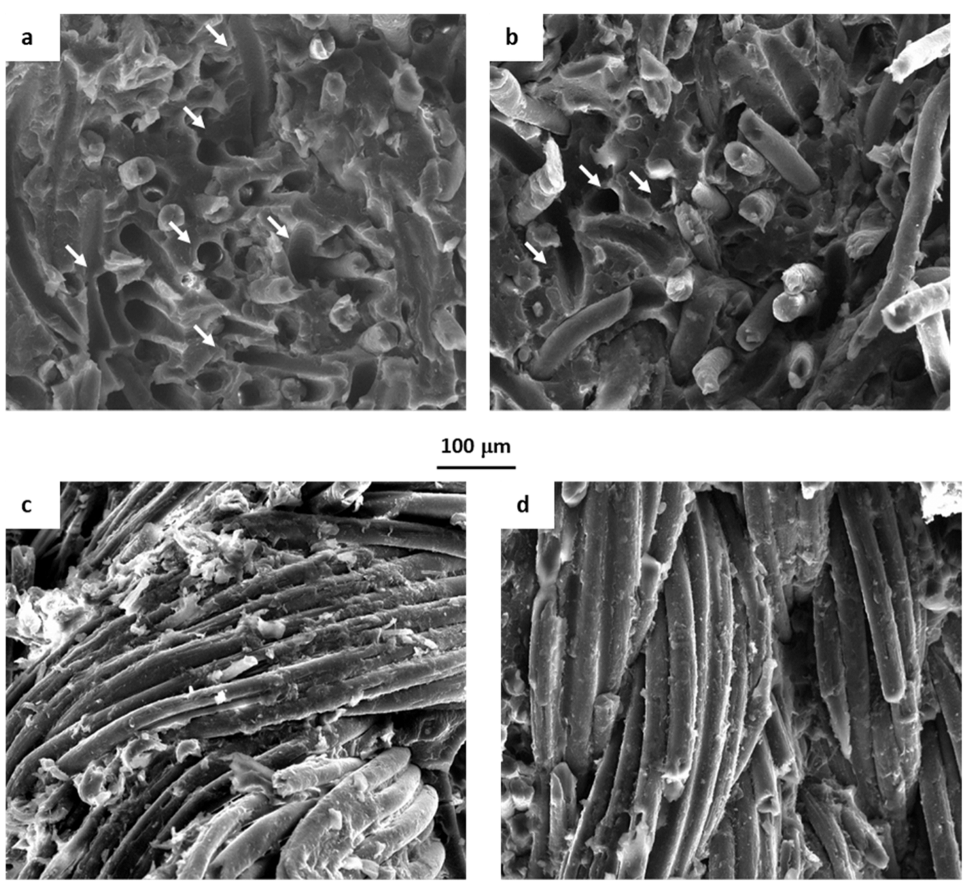

Fig. 6. SEM acquisitions of surfaces fracture; a): FNEPS50; b) FNABS50; c) LFNEPS; d) LFNABS.

obtained with impact test were analyzed by using Scanning Electron Microscopy. SEM micrographs of composites prepared by grinding and laminate approaches containing 50 wt% of fibers are shown as an example in Fig. 6.

Overall, the morphological investigation well represents the different morphology of the samples prepared by the grinding or lamination approaches and justify the different results obtained by flexural and impact tests for laminates.

Indeed, in the case of the samples prepared by grinding approach, low sized particles obtained by grinding of FNs, despite their very high amount, appear homogeneously distributed in the polymer matrix. Pull out phenomena are observed, evidenced with narrows in Fig. 6a,b, as a consequence of the mechanical load applied to generate the fractured surfaces, indicating a non-optimal matrix/ filler interfacial adhesion. This is particularly true in case of EPS matrix, while in the micrograph of ABS based composite (Fig. 6b), some more coverage of the fibers by the matrix polymer can be observed. Filler size and preparation approach also seem to affect the morphology of the resulting composite. In fact, a different morphology was observed for the laminate composites (Fig. 6c, d)., characterized by the presence, within the polymer matrices, of FNs consisting of knotted multifilament yarns. For these samples, the long nylon 6,6 fibers appear still twisted in the multifilament yarns and no significant fiber breaking and/or detachment phenomena are observed as a consequence of the load applied to fracture the samples, well explaining better flexural and impact strengths of laminates. This finding can be justified considering that short, ground FN fibers have a much higher surface, which makes harder to obtain an efficient wetting and a good dispersion of the fibers during mixing.

3.6. Impacts of the fishing net recycling

The determination of the cost-effectiveness of plastic pollution mitigation strategies is a complex process that requires the determination of the cost of the approach, its efficacy, and the benefits it produces (Cook et al., 2017). In this paper, the economic impact of the recycling approach developed for the fishing net was qualitatively esteemed following the approach used by Beaumont et al. (Beaumont et al., 2019) for which the economic costs of marine plastics was determined in relation to marine natural capital considering the ecological, ecosystem service and social and economic impacts of plastic waste.

In this respect, the recycling processes proposed in this paper involves sorting, cleaning, grinding/or cut of nets, dissolution, drying of polymeric matrix and compression molding. These steps induce advantages related to the decrease of fishing net wastes dumped at sea and in landfills and the overall increase of the material recycling, with consequent decrease in the usage of raw material and decrease in CO_2 emissions for the realization of new materials. In fact, fishing nets when discarded or lost in the ocean were considered with a high negative impact on marine species, including mammals, birds, fish, and invertebrate, due to the mortality and putative mortality they cause from entanglement. A complete analysis of species impacts, documented in removed derelict nets, was reported by Drinkwin et al. (Drinkwin et al., 2023). In this respect, recovery and recycling of fishing nets produce an ecological benefit. Additional environmental benefit of the recycling of fishing nets is related to a reduction of secondary microplastics release. Considering degradation phenomena, occurring on nets lost in the marine environment or during their storage induce the generation of secondary microplastics including microplastics of fibrous shape with a highest ecological impact (Welden and Cowie, 2017).

As concerning the ecosystem service impacts, a high critical service is represented by fishing and aquaculture industry where nets are largely used and, directly, influence the productivity, viability, profitability and safety of the service while, indirectly, affect nutrition and the wellbeing of the population (Golden et al., 2016). A negative impact is also accounted for the recreation activities since the storage and/or loss of fishing nets at the end of life affect the recreational users of coastlines as well as safe recreational navigation with an increase of loss of tourism and of the economic efforts to dismiss nets. Thus, the recovery and recycling of fishing nets at the end of life contribute to the conservation/restoration of the ecosystem service.

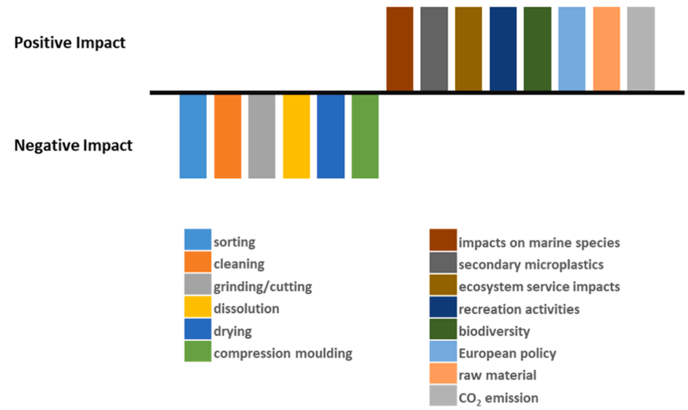

Fig. 7. Negative and positive impacts associated to the recycling approaches.

Beyond the ecological and service impacts described above, the presence of nets in the marine environment affects also the biodiversity. Lost nets can trap several species or be a substrate for the colonization and growth of other organisms and the current and wave actions are responsible for the transporting of alien species, microalgae and alteration of habitat (Gilman et al., 2021). Finally recycling approaches are in agreement with European Commission goals aiming at reaching by 2025 a reduction of abandoned fishing net of 50% and a 15% recycling target (Richardson et al., 2019).

In Fig. 7 the negative and positive effects obtained by recycling approaches of fishing nets at the end of life are reported.

In this scenario, it emerges that the environmental benefit obtained by the recycling approaches provide an incentive for the development of new routes to produce materials using fishing nets at the end of life.

4. Conclusion

In this article, a sustainable, cost effective technological approach aiming at recycling nylon FNs at the end of life was evaluated. Two different routes were explored to recycle FNs as reinforcement in EPS and ABS matrix composites: grinding approach and lamination approach. With the first approach, it was possible to obtain high load composites with up to 80% of short fibers, exploiting the solvent assisted fluidification of the polymeric matrices; however, above 60 wt% some inhomogeneity in the distribution of fibers after compression molding were observed. ABS based composites showed in general a better mechanical behavior at high FN content with respect to EPS materials, due to a better adhesion between the phases. Laminates, prepared with 50 wt% of continuous FN, showed slightly better flexural properties and a remarkably high impact resilience, benefitting from the different morphology of the fibrous reinforcement. The obtained materials exhibit mechanical parameters comparable to commercial PS and ABS, as reported in datasheets and handbooks. The obtained results demonstrate that the proposed process represents an effective and sustainable valorization strategy for lost, abandoned or discarded FNs.

Declaration of Competing Interest

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

Acknowledgments

This work was realized in the framework of the Project – Biomonitoraggio di micro e nanoplastiche biodegradabili: dall'ambiente all'uomo in una prospettiva one health (BioPlast4Safe) – with the technical and economic support of the Italian Ministry of Health - PNC.

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