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Review

Exploring the Potential of *Posidonia oceanica* Fibers in Eco-Friendly Composite Materials: A Review

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Abstract: The growing demand for sustainable materials has driven the exploration of natural fibers as eco-friendly alternatives to synthetic reinforcements for composites. This study investigates the potential of *Posidonia oceanica*, an abundant marine biomass, which is often driven to be stacked on the backshore and used so far for energy recovery and low-value applications, as a filler and possible reinforcement in cementitious and polymer composites. Most applications of Posidonia are concentrated in the Mediterranean area and focused on the construction industry. However, its introduction in polymer composites, especially as a source of cellulose or in combination with the use of bio-based matrices, can also be proposed. With this aim, the physical and chemical properties of *Posidonia oceanica* fibers need to be characterized, and their compatibility with various matrices needs to be evaluated. Experimental results demonstrate that *Posidonia oceanica* fibers, especially when treated with alkali and silane, or combining both treatments, can exhibit mechanical properties quite comparable to other natural fibers, namely to those obtained from grass species. As with any other type of waste, yet with more interest for its wide accumulation over the coastal line, the use of *Posidonia oceanica* in composites may contribute to reducing the environmental footprint of these materials, aligning with circular economy principles. This review highlights the dual benefits of utilizing marine biomass by advancing material sustainability while not being detrimental to coastal waste management.

Keywords: *Posidonia oceanica*; natural fibers; fiber-reinforced composites; sustainable materials; bio-based composites; circular economy

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1. Introduction

1.1. Context

The concern over the scarce sustainability of fiber-reinforced composites has brought forward some actions, which are slowly progressing among various processing difficulties, such as the prospected recycling of thermosetting matrices, which are considerably used in fields such as the marine industry [1]. Another possibility is the use of secondary raw materials for composites' production, which has recently become a strategy of interest for reducing the environmental impact of these materials while addressing issues concerning the disposal of refuse [2]. In particular, the use of natural, and specifically lignocellulosic, fibers as eco-friendly reinforcements has emerged as a promising solution, combining mechanical performance with sustainability, forming the increasingly wide category of

natural fiber composites (NFCs) [3]. The geometries and the origins of these fillers are gradually expanding on the basis of local availability considerations, together with their adaptability to different matrices and more generally hosting materials [4]. Also, the parts of the plant these materials originate from can be the most various, from the stem to the leaf and the fruit hair, but even the bark or the seeds have been considered, of course with very varying availability and properties [5]. The derivation of these composites from any vegetable waste recently gave rise to the definition of "biomass-derived composites". This emphasizes their origin from any natural by-product and particularly their combination with bio-based polymer matrices, synthesized from polysaccharides plasticized in various forms [6]. Botanical species offering fillers for composites are now countless. A few among these represent large markets (e.g., hemp, flax, sisal, jute), where an economical system based on fiber products can really be conceived. Considering the whole of the crops involved for natural fiber production in composites, fibers can be obtained from land cultivations and specifically, depending on the species, from basts, leaves, fruit hair, seed hair, grass, yet also wood or bark, or from the sea, as is the case for algae. A more limited market exists also in composites for animal biomass, such as for wool, silk, or animal hair in general.

In most cases though, biomass used in composites does represent a by-product (if not waste) of other production systems (food, paper, and forestry, to name a few). When this is the case, it is most likely that only short stretches of lignocellulosic material are available, albeit suitable for applications such as 3D printing [7] or random short fiber composites. Biomass adapted for application in composites is also available in the sea context, in particular, based on algae, which can be used both as the reinforcement of composites [8] and as their matrix in the form of alginate [9]. As far as the use of algae in composites is concerned, more studies are given below.

Sea-derived materials have obtained some attention recently as a substitute for other ceramics (e.g., calcium carbonate), or lignocellulosic material [10]. Examples of these materials, which may be of interest and have actually been proposed for potential use in composites, are given in Figure 1. As a result of this activity, a number of studies exist on specific algae in composites, such as red algae [11], *Ulva lactuca* for heavy metal removal [12], and brown algae in cassava starch biocomposites [13]. The use of other sea-derived materials in composites concerned shrimp shell waste in recycled polypropylene [14], and general seashell waste, where an obvious competition arose, given its nature, between its uses in biocomposites and bioceramics [15].

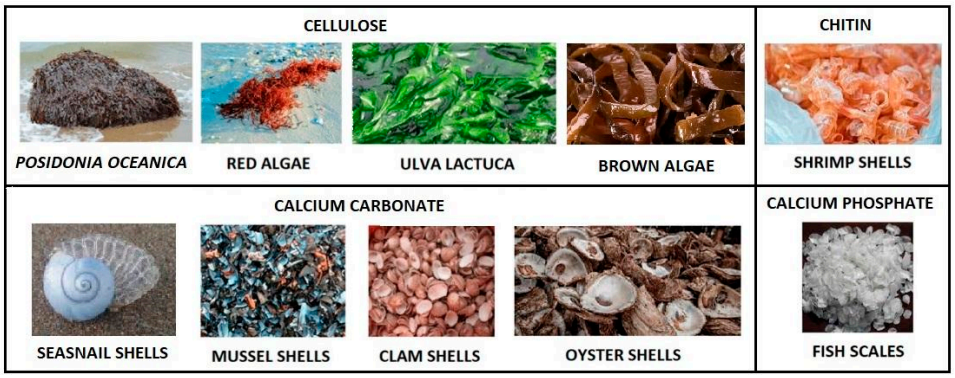


Figure 1. Sea-derived materials for use as secondary raw matter in composites.

Within this thriving context, *Posidonia oceanica*, a marine species endemic to the Mediterranean Sea, while sometimes reported as "alga" [16], though being a rooted plant [17], has recently garnered interest as a potential natural reinforcement for composites. Renowned for its ecological importance in marine ecosystems, *Posidonia oceanica*

generates substantial biomass, particularly as dried seagrass washed ashore. Ample discussion has gone on in recent years on which portion of it can be reused on the shore itself, e.g., to prevent erosion of the beach or of neighboring ones, hence considering a 0 km perspective [18]. On the other hand, a number of possible fields for the use of *Posidonia oceanica* leaves have been considered, also not directly related to the extraction of fibers from them. These include, in particular, the removal of dyes, whose fixation was improved through carboxymethylation of Posidonia biomass [19], and of antibiotics, namely tetracycline, from water [20]. Another possibility, which has been investigated, is the conversion of dead Posidonia leaves into the preparation of fluorescent carbon dots, a multifunctional nanomaterial [21]. By grafting Posidonia with specific biopolymers, such as succinic anhydride, it is also possible to obtain chelating materials to adsorb heavy metals, e.g., lead, for the purpose of their removal from water solutions [22]. With the combustion of dried Posidonia leaves, the recovery of rare earth elements (REEs), in particular, trivalent cations of lanthanum, dysprosium and neodymium, through adsorption on the obtained biochar, has also been proposed [23].

It has therefore been highlighted that, despite all the potential applications, the remaining amount of this abundant resource, often treated as waste, presents an opportunity for innovative applications, in materials but also as providers of chemicals and extracts, while contributing to circular economy principles [24]. Posidonia biomass can be schematically divided into materials of two different geometries, egagropili balls and loose leaves, also defined as tapeweed, in some cases studied separately to evaluate their distinct properties [25]. These include the potential production of fibers at different scales, for papermaking, cellulose derivatives for various industrial applications, biotechnological applications centered on waste remediation, and the production of nanocomposites, bioplastics, and general biocomposites [26].

This review aims to provide a comprehensive overview of the state of the art regarding the use of *Posidonia oceanica* in composites, including cementitious composites, polymer biocomposites, and nanocomposites. Drawing from recent studies, it examines key aspects, such as the physical, chemical, and mechanical properties of *Posidonia oceanica* fibers, their compatibility with various matrix systems, both ceramic and polymeric (synthetic and bio-based), and their potential applications in diverse sectors. By synthesizing findings from existing research, this article seeks to position *Posidonia oceanica* as a grass-derived fiber valuable for bio-based composites and to identify avenues for future investigation. In doing so, it contributes to the broader discourse on sustainable development and the realistic integration of natural resources into composite engineering.

1.2. Review Method and Structure

This review was conducted to synthesize and critically analyze existing studies on the potential of *Posidonia oceanica* fibers for use in cementitious and polymer composite materials. The scope of the review included examining the physical, chemical, and mechanical properties of *Posidonia oceanica* and its integration with various matrices (ceramic, polymer, bio-based or not). The principle that inspired this review is that, in those cases where the collected Posidonia is demonstrated not to be possibly kept in coastal areas for environmental reasons or reintroduced in the sea, it can enter the domain of secondary raw materials. If this is the case, it can be used in materials according to the waste hierarchy prescribed in Article 4 of the European Commission 2008/98 directive. Beyond this, reasoning according to end-of-waste (EOW) criteria, its integration into durable materials has been considered as a more effective strategy than its bare composting process, which has been proposed in earlier studies [27].

With this in mind, inclusion criteria focused on studies that explicitly investigated the properties, processing methods, and applications of *Posidonia oceanica* in the form of fiber, extracted from egagropili or tapeweed leaves. In this respect, an initial matrix of research has been developed, as produced from the diagram indicated in Figure 2, which starts from all the publications mentioning the word Posidonia yet refines that by cross-correlating it according to four criteria:

1. Its accumulation and then possible role of waste/refuse (black criterion);
2. Its potential as a natural fiber (brown criterion);
3. Its function in a durable material, so in terms of strength (red criterion);
4. Its coupling in a composite, hence providing an interface with the matrix (orange criterion)

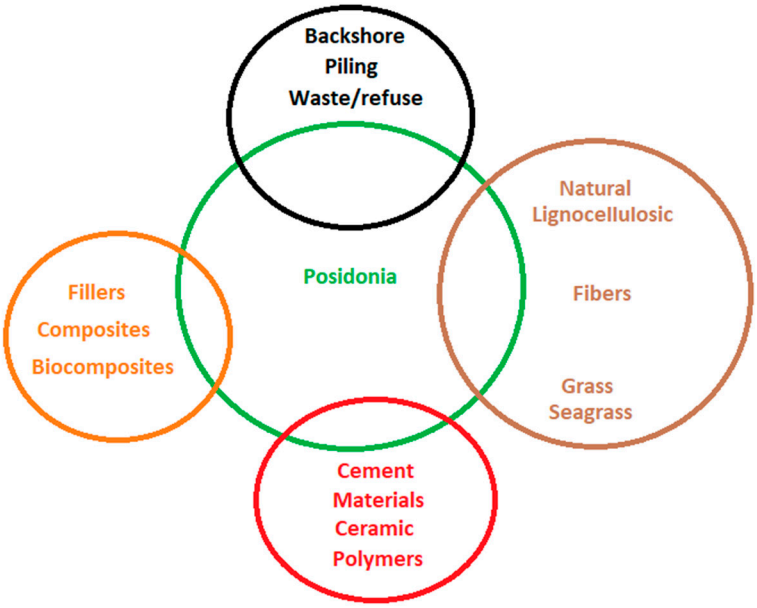


Figure 2. Initial selection diagram for the publications.

This process was carried out by having Google Scholar as the first reference for bibliographic research, yet integrating this knowledge with Web of Science and Scopus when necessary. It needs to be mentioned that all the literature included in this review has been re-screened for relevance by reading the whole papers. This specifically applies to the case when the abstract did not give sufficient indications for the Posidonia considered to have been collected in the backshore and in conditions (e.g., contamination, overpiling with extraneous materials) that would not enable its reintroduction at sea.

A publication date range of the last 15 years was prioritized, to which the largest majority of studies on Posidonia applications into composites belong, although earlier works that tried to discuss the Posidonia waste issue were also considered where relevant. It is also worth considering that Posidonia fibers are strongly electrostatic, which also assists the agglomeration of egagropili and promotes their potential in some applications e.g., as biosorbents [28]. This hinders sometimes their application in composite resins, so most of the initial studies aiming to revalorize this resource concerned its application in cementitious materials, and more generally in the building industry. For this reason, it has been considered valuable to first deal with this relatively easier application, and only subsequently to concentrate on the production of polymer composites. As a consequence, when categorizing data into thematic sections, fiber properties and potential are discussed in Section 2, the fibers' basic applications as paneling materials and cementitious composites are discussed in Section 3, and specific developments on polymer composites and nanocomposites are dealt with in Section 4. A discussion on future scenarios is presented in

Section 5. Each study was critically evaluated based on its methodological rigor, relevance, and contribution to the field. Common findings, discrepancies, and research gaps were identified to provide a comprehensive understanding of the current state of knowledge and guide future research directions, especially to understand the point at which the use of Posidonia waste in materials could be viable.

This methodology ensured a robust and systematic approach to analyzing the existing body of literature, highlighting both the potential and the challenges of integrating *Posidonia oceanica* fibers into eco-friendly composite materials.

1.3. The Question of Posidonia Piling on Backshore

It is recognized that concern has been expressed over the oscillation of the quantity of *Posidonia oceanica* in the marine environment due to sea exploitation, together with climate change and the invasion of exotic species [29]. Table 1 indicates some marine biology studies that concentrate on local cases, highlighting the importance of preservation of the environmental system centered on the presence of rooted Posidonia on the sea floor and of the related accumulated concentration of dead biomass, defined as "banquettes" on the shore. Technically, a banquette represents neither a sediment (to be compulsorily preserved) nor a waste (to be removed), yet a mixture of the two, also including, if carried on the backshore and left there over time, some amount of extraneous materials.

Table 1. Studies on preservation of banquettes.

Location	Indications	Ref.
Nueva Tabarca Island (Alicante, Spain)	The material of the banquette, if not consumed by terrestrial detritivores, would be exported further away inshore, possibly being mixed, if not contaminated, with other materials	[30]
Calabria (Italy)	Passing from simple beach litter removal to maintenance would reduce wave energy and the erosion process	[31]
Zarzis (Tunisia)	Repositioning of the banquettes as a good practice needs to be planned and executed appropriately so as not to push it to the extremes of the beaches, therefore practically impeding its preservation	[32]
Sinus Peninsula (Sardinia, Italy)	Banquette removal leads to silicate and carbonate sediment loss and reduces both the barrier's thickness and the beach's resilience to storm events	[33]

From the indications above, the use of Posidonia in materials would only involve the excess of the banquette pushed in the rear area of the beach and also possibly contaminated, which therefore cannot be thought of as possibly being reintroduced in the sea by the tide. Regarding the dimensions of this excess, and the generalized possibility of beach management that would allow maintaining the whole of the banquette ashore, the literature appears contradictory. This review does not obviously stand on either of the two sides, only reporting the potential evidence for the application of Posidonia residues in composites and more generally for use in materials.

In areas such as the Adriatic Sea and its shores, a distinction needs to be made between completely protected areas and those that are not possibly so, since decomposition of the banquette does represent an issue over time. Specific studies were carried out on the Tremiti island system [34], as far as full preservation is concerned. In other zones with no specific environmental constraints, Posidonia banquettes do reach considerable heights on the shores and are treated as "zero km" waste, ending up being disposed of as compostable material or for energy recovery, if not landfilled as natural residues, or proposed as a source of green hydrogen [35]. It has also been suggested that in terms of energy efficiency, the high lignin content of Posidonia does not appear to guarantee a facile production of bioenergy by anaerobic digestion, leading to a substantial downcycling of

the material [36]. In another study, backshore residues of Posidonia were measured to have a lignin content of up to 34%; this offered some surplus of energy, depending on the implant's size, between 22 and 35% by a dual method, including acidic thermal analysis and subsequent anaerobic digestion [37]. Other than from the beaches, Posidonia residues are also accumulated and usually not removed from the sea bottom in enclosed coastal areas, e.g., from harbors, coming to considerable thicknesses even in the order of meters. The issue of disposal was also discussed in this case, in particular in [38]; the aspect of typical refuse is depicted in Figure 3. Various options were discussed, such as composting, once the chlorine content was reduced, and heavy metals, which need to be measured as well, within limits. Regarding the latter aspect, a study on the Posidonia residues obtained from the Murcia coast (Spain), aimed at their possible use as a forage replacement for ruminants, indicates their suitability for the application regarding mineral contents, but such an outcome cannot obviously be generalized [39]. For higher-level uses, construction aggregates or interior finishing materials were suggested, in some cases possibly even without the removal of chlorine, therefore more concentrating on polymer-based blends than on concrete or gypsum, which can be degraded by chlorine. These indications suggest that the potential for the use of Posidonia residues in the field of composites does exist, but it can only be examined depending on local situations. Moreover, given also the limited interest in energy recovery and biogas production, the recycling of Posidonia fibers into durable materials, such as polymer resin composites, represents an option and, as a matter of fact, has received scattered, though diffuse, attention in the last two decades at least.



Figure 3. Sea bottom sediment from Sperlonga port (Latium, Italy) (elaborated from [38]) (reproduced under Creative Commons 4.0 license).

2. Posidonia Oceanica: Characteristics and Fiber Potential

2.1. Morphological Characteristics of the Residues from Posidonia Banquettes

Banquettes of *Posidonia oceanica*, being constituted by different proportions of leaves and sediments, normally siliciclastic and carbonatic in similar proportions [40], accumulate on the beach and in proximity to the coast. As observed in Section 1, it is widely recognized that, when administered in terms of an "ecological beach" model, Posidonia banquettes need to be preserved by being kept ashore as much as possible, for their benefits in terms of coastal protection and maintenance of biodiversity [41]. In a more general view, it is also evidenced that their carbon sequestration capacity contributes to attributing a role in climate mitigation strategies to banquettes [42]. It is recognized that the residual amount of living matter in Posidonia banquettes includes a significant amount of carbon and nitrogen, which may further contribute to biodiversity preservation [43].

In many cases though, Posidonia banquettes comprise not only sand, sediments, and other sea-originating materials, such as algae, but are also interspersed with microplastics and other sea-extraneous waste [44]. In general terms, the farther from the shore the banquettes, the lower is the amount of leaves they include, also because a part of these, which end up on the foreshore, may be subsequently dragged back into the sea [45]. It is precisely the *Posidonia oceanica* leaves that lay for a long time on the backshore and are

likely to remain on the strand that might represent an issue for their biological degradation and progressive accumulation as a biomass residue. The cumbersome process of removing extraneous waste from it does not make their disposal in the sea practical (not to say sustainable), so in practice, the whole of the Posidonia-loaded litter is piled up in informal disposal sites.

In particular, the removal of stranded Posidonia delivering it from accumulated undifferentiated refuse is impeded by its tendency to aggregate in balls (egagropili) that become easily contaminated by other material that becomes trapped into them, especially when they remain in the backshore area for long periods of time [46]. Posidonia leaves have a typical tape-form aspect and can grow to a length of ca. 1 m, while the plant has rhizomes growing parallel (plagiotropic) or perpendicular (orthotropic) to the seabed [47] and ramified roots, which effectively adhere to the substrate [48].

2.2. Chemical Composition and Properties of the Fibers

From the *Posidonia oceanica* leaves, fibers can be extracted, which possess a significant cellulose content: some difference in this respect has been observed between the egagropili and the loose fibers (61.8% and 57.1% holocellulose, respectively), which was reflected in a similar presence of lignin (29.8% and 24.7%, respectively) when chemical extraction studies were performed [49]. In contrast, another study reported a higher value of cellulose obtained by ionic chromatography, which represented 70.2% of the total weight, with 19.6 wt.% of lignin [50]. However, this confirmed a higher lignin content than in most common bast fibers, yet evidently resembling some grass types, such as esparto (*Stipa tenacissima*), which proved suitable for introduction in cement rather than in polymer composites for this reason [51].

It is also suggested that the formation of balls results in a similar agglomeration of calcium carbonate and silico-aluminate, while silica is normally easily separated and does not solidly bond to the egagropili [52]. Fibers extracted from egagropili are often shorter yet still sufficiently straight and with an evident fibrillar structure, such as those represented in Figure 4 at two different magnifications [53]. On the other hand, the non-negligible lignin content in egagropili, evaluated as being approximately equal to 34% by Mnafki et al., 2024, confirming the above data, also suggested the need for a delignification process in view of other potential applications, or else the application of a biorefinery concept, which could even exploit the large ligneous fraction of this biomass [54]. Other than the particular alcoholic lignin composition, rich in guaiacyl and less in syringyl, the high potential of carbon sequestration of *Posidonia oceanica* was also suggested by its abundance in *p*-hydroxybenzoic acid which allows attachment to the side-chain hydroxyls [55]. This has been discussed already in terms of the climate change effect, which also suggests that Posidonia is preserved as much as possible in the sea.

The excess Posidonia, which ends up in the backshore region, can be, as for its chemical composition, compared with other leaf fibers with lignin content above 20%. In particular, a study on banana leaf residues elicited a similarity with Posidonia in lignin content and suggested their potential for the production of micro- or nanofibers, also in terms of their very large dimensions and the relative yield of the pulping process [56]. In general terms, high-lignin leaf litter, especially in the Mediterranean context, has been studied to evaluate its degradation patterns in terms of nitrogen cycles, particularly for hairy rockrose (*Cystus incanus*), holm oak (*Quercus ilex*), and myrtle (*Myrtus communis*) residues [57]. A high lignin content is normally not very suitable for practices such as composting and vermicomposting since it clearly reduces biodegradability and often also keeps the C/N ratio at a lower level than required [58]. Despite this, the use of Posidonia peat for compost has been tried in low amounts, demonstrating to be of sufficient performance, while pushing the

process further was unsatisfactory, especially due to the presence of boron in the material, though some crops, such as tomato, were revealed to be sufficiently adaptable to that [59]. Further investigations indicated that a distinction in terms of morphological and chemical properties can be made between egagropili content and loose Posidonia fibers, indicating these as a bulking agent and a generic green litter, respectively, in the composting process, to which this material can only be added in very low quantities [60]. In this situation, a possible competition of the use of Posidonia as a source of green fuel is to be expected and has been proposed in a number of situations, e.g., in combination with exhausted frying oil [61]. Notably, a comparison with lacustrine alga and white pine indicated that, unlike the competitors, biofuel from Posidonia had a comparable yield to that of woody biomass, and relevant biochar offered suitable properties for soil use, namely its alkaline pH (10.75), while it had a stability similar to that of white pine [62].

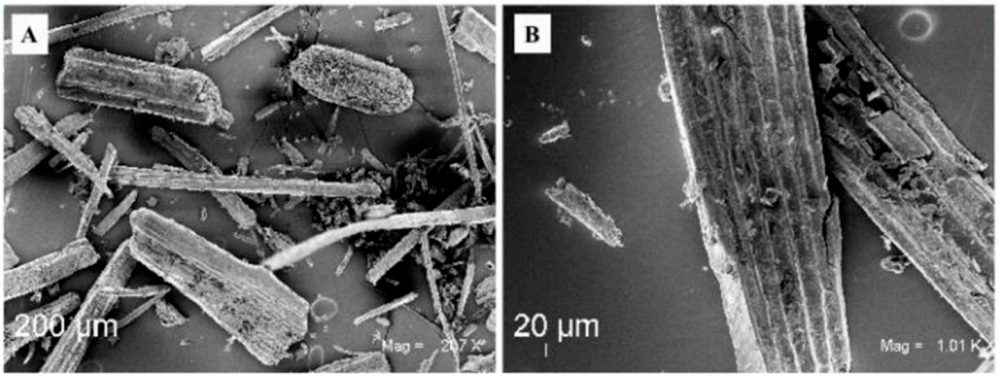


Figure 4. SEM pictures of egagropili fiber collected on Poetto Beach (Cagliari, Sardinia, Italy) (**A**) at low magnification (207×), and (**B**) at high magnification (1000×) (elaborated from [53]) (reproduced under Creative Commons Attribution (CC BY) license).

In this sense, however, the specificity of Posidonia leaf litter stands clearly out since it combines a high lignin content with a relative fineness of fibers obtained. The density of these has been reported to be equal to 1.15 g/cm^3, therefore considerably lower than other fibers that are almost entirely cellulosic, such as jute, kenaf, hemp, or flax, which have density in the range between 1.3 and 1.5. Also, an average diameter of 238 microns was determined for the technical, hence potentially textile, fibers from tapeweed [63]. They present a flattened section with diffuse and very variable internal voids, and they are externally covered, even after the minerals coming from shore contact are washed away, by waxy and rubbery matter, having, as far as a possible textile application, a linear density of 7.31 tex and a tenacity between 5.31 and 11.19 cN/tex [64], which is therefore quite far from that of esparto fibers (29.24 cN/tex), often referenced as similar [65]. This appears to barely exclude any possible textile application of Posidonia fiber. In [64], a Taguchi analysis was also performed to optimize the effects of sodium hydroxide treatment of Posidonia fibers with the three parameters of NaOH concentration, time, and temperature on yield, aspect ratio, linear density, tensile strength, and elongation. Optimal properties were obtained when the fibers were treated by being immersed at 100 °C for 45 min in a 0.5 sodium hydroxide solution. This is in line with what is observed in the case of other leaf fibers that are suitable for that use, such as banana ones, and can be improved by the application of an adapted chemical treatment [66]. It can be noticed that Posidonia fibers, even once extracted, tend to be largely prone to fibrillation and to offer kinks during flexure, as is observable in Figure 5.



Figure 5. Typical aspects of Posidonia fibers extracted from egagropili (image by the authors).

2.3. Acoustic and Thermal Characterization of Posidonia Fibers

Posidonia fibers were also characterized for their acoustic and thermal properties to assess their potential application in bio-based insulating materials. As regards acoustic characteristics, the Posidonia sea habitat is important to be preserved as it hosts a larger biodiversity than the sandy sea bottom, because of easier sheltering and food opportunities, and also hosts a considerable richness in biophonic components and therefore sound-producing organisms [67]. The unfortunate stranding of Posidonia, often contaminated with extraneous materials and therefore irreversible, does offer, after careful separation, an amount of secondary raw matter, which can possibly be used as a natural (a) acoustic or (b) thermal insulator.

(a) Acoustic characterization was carried out with fibers extracted from egagropili collected in North Sardinia beaches, measuring the frequency response of the board prototypes according to the range of densities effectively found in the Posidonia balls, hence between 50 and 200 kg/m^3. In this context, the Posidonia boards with higher densities, i.e., 100, 150, and 200 kg/m^3, were revealed to be able to favorably compete against 50 kg/m^3 mineral wool and polyester boards, even peaking in the 800–1000 range and around 4000–4500 Hz [68,69]. This qualifies Posidonia among waste short fibers that offer this potential, such as, in particular, tea leaves, coffee skins, esparto leaves, pineapple leaves, and *Grewia optiva*; in all cases, the combination of a large amount of porosity and a significant quantity of lignin ensures good acoustic results [70].

(b) Another possibility is the use of Posidonia residues for the scope of thermal insulation; some experiments in Sicily confirmed the role of the Posidonia banquette in terms of soil bio-insulation, able to provide limitations to shore heating and therefore more generally to ground temperature [71]. In case of the need for banquette removal, as is often the case, for beach setting-up for the summer season, transferring Posidonia into a soil container made by fascines (vine shoots) allowed an average soil cooling of around 5 °C (26.4 vs. 31.2 °C) for the maximum temperatures reached over a year in an experiment. This suggests the potential for this application, namely for the insulation of buildings situated in areas where the presence of Posidonia represents a continuous occurrence, for which a thermophysical characterization of the fibers is necessary. In particular, the determination of thermal conductivity with various densities has been assessed, which demonstrates that it decreases to an optimal value. This was measured in [72], using fibers cut down to a size of 5 mm, as being in the region of 20 kg/m^3, offering a thermal conductivity below 0.05 Wm^{-1}K^{-1}, therefore not far from what has been obtained, e.g., with cotton wool and expanded cork. More precise indications are offered in Figure 6. In practice, the effect of chemical treatment with sodium hydroxide at 2% concentration was limited, though more significant at higher densities for reducing thermal conductivity.

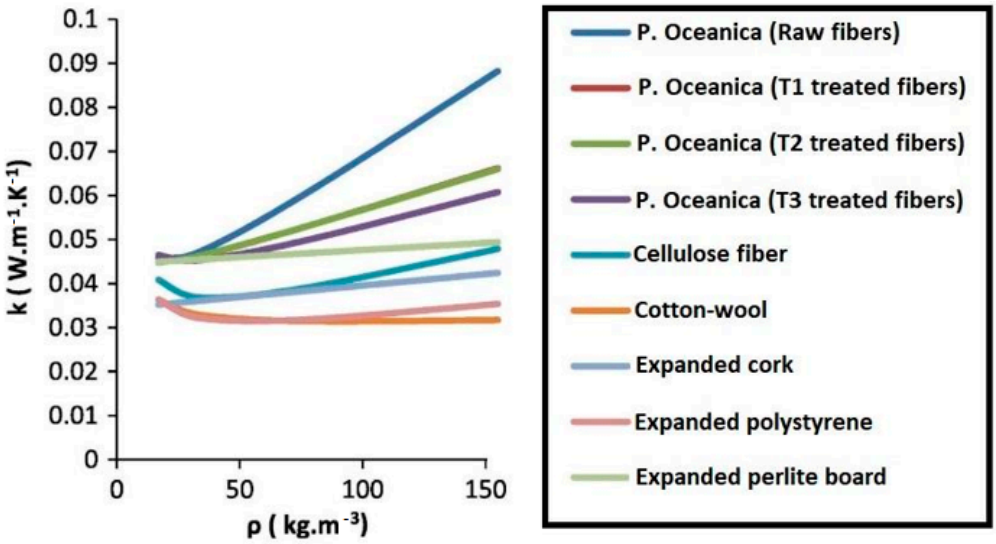


Figure 6. Thermal conductivity (k) as a function of density (ρ) for untreated and treated Posidonia fiberboards vs. boards of other materials. Treatment T1: fibers are immersed in a 2% NaOH solution for 2 h at 80 °C. Treatment T2: fibers are immersed in a 0.75% NaOH solution for 1 h at 100 °C. Treatment T3 repeats treatment T1 on already treated fibers (reproduced with permission from [72]).

3. Proposals to Bind Posidonia Fibers into a Material: From Wood-Replacement Boards to Cementitious Composites

3.1. Use of Binders with Posidonia: Wood-Replacement Boards

The relative success in thermal and acoustic characterization and the improvement obtained by chemical treatment also suggested the integration of Posidonia materials. Following this, the question of the binder is posed: in principle, a sustainable and bio-based one should be used. A proposal for the use of cornstarch binder is presented in [73], finding out that the thermal conductivity varied between 0.052 and 0.067 $Wm^{-1}K^{-1}$, yet the introduction of more binder in volume (up to 30%) affected the moisture capillarity in the board. The classical alkali treatment of Posidonia fibers using sodium hydroxide (NaOH), while improving their geometrical regularity, only marginally affected their thermal properties, yet it had some effect on the flexural properties of the boards, which decreased with Posidonia fiber content [74]. A possible hybrid composite board produced by mixing 25% Posidonia fibers with 75% wood fibers using methylene diphenyl diisocyanate (MDI) offered a compression strength very variable in the region of 5–7 MPa and lower than required by European standards, with a density around 0.8 g/cm^3 [75]. This highlighted some promise in the use of binders to propose Posidonia as a replacement for wood in boards, which paved the way for the introduction of Posidonia as a filler of a composite material. This occurred first with cementitious matrices for the building industry and then also with polymer ones for more general purposes, to be able to potentially include Posidonia among the lignocellulosic fibers of current use in biocomposites.

The use of Posidonia waste as the replacement for wood boards has been proposed, namely for improved sustainability by using secondary raw materials. This was considered advantageous in terms of carbon footprint over bare combustion of these materials, such as that proposed in [35], or the production of syngas from their decomposition process [76]. In terms of energy recovery, wood chips appear as a constant reference for assessing Posidonia waste performance [77]. Adhering to these quite narrow objectives (i.e., avoiding Posidonia disposal by incineration or gasification), it was deemed not strictly necessary for the manufacturing of wood-replacement boards to select Posidonia leaves precisely in terms of dimensions and geometry, so that even the extraction of the fibers from these would be unnecessary. In [78], leaves were kept to a length of 50–150 mm and a width

of 8–10 mm, dried down to 6–7% moisture, even preserving the natural pH, i.e., 8.2, and incorporated into wood boards in different percents, using a urea–formaldehyde resin in an amount of 7% over dry weight. The best thickness control was achieved within a 50:50 Posidonia–wood chip board, though at the expense of the performance obtained. It was suggested that alternative bonding resins, such as isocyanate, might address this issue, though the sole value of introducing Posidonia leaves would be using an abundant waste available ashore and normally disposed of in the specific situation (Greece) in landfilling. It is therefore suggested that petrochemical resins are initially used for the fabrication of these boards, though partially bio-based ones are gradually introduced, such as bio-epoxies, which also represent an important trend presently in the composite industry [79]. The use of a bio-epoxy with a renewable content not inferior to 55% enabled the production of hot press molded panels with up to 70% *Posidonia oceanica* fibers with a length between 2 and 8 mm. Fiber content did result in a reduced flexural modulus and strength with respect to the bare resin. However, a significant improvement in Shore D hardness was reported by different fiber treatments using, as in other cases, sodium hydroxide (alkali treatment), yet the Charpy impact performance was also even enhanced when applying a combination with silane, more successfully with (3-glycidyloxypropyl)trimethoxysilane (GLYMO) [80]. Wood replacement boards were obtained and are shown in Figure 7.

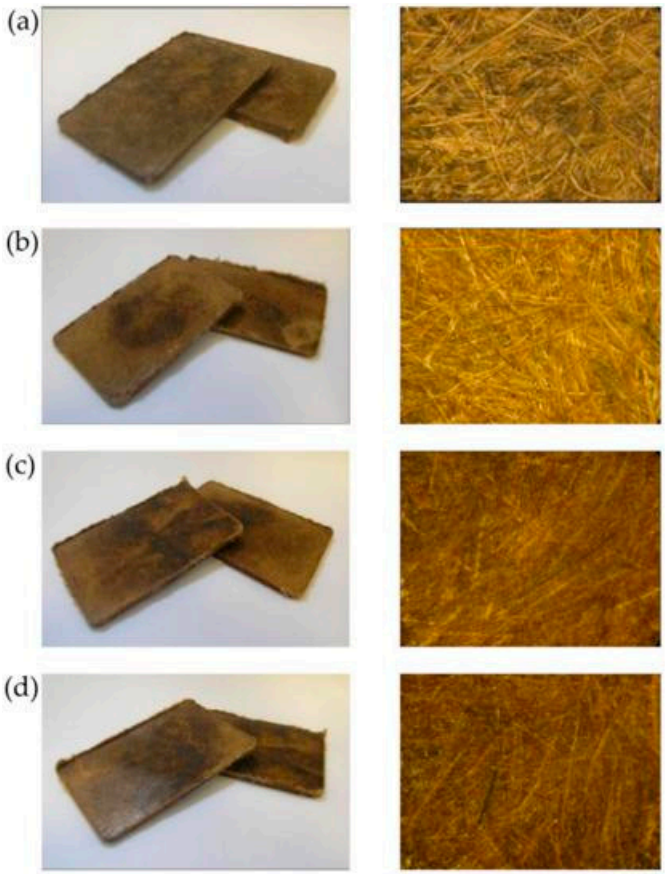


Figure 7. Optical images of fiberboards (**left**) and their surface appearance (**right**) with 70% Posidonia fibers: (**a**) untreated and subjected to different chemical treatments, (**b**) NaOH, (**c**) NaOH + aminopropyltrimethoxysilane (APTMS), and (**d**) NaOH + (3-glycidyloxypropyl)trimethoxysilane (GLYMO) (reproduced under Creative Commons 4.0 from [80]).

3.2. Cementitious Composites

The previously mentioned studies on the acoustic and thermal insulation properties of materials including Posidonia fibers quite well fit the picture of their introduction into

cementitious composites as the fibrous addition, e.g., to cement, clay, or gypsum. The various options that are available and were explored in the literature are described in Figure 8. It is not unusual that grass fibers, and therefore potentially also Posidonia, are used as fillers in cementitious composites, normally in a short randomly oriented disposition. For this application, an obvious competitor is again esparto (*Stipa tenacissima* or *Lygeum spartum*), which has a long tradition of general use in composites in the widest possible sense, though mainly with calcium carbonate-based matrix [81]. A comparative study on these two grasses in cement is also available in [82], which highlighted the fact that fiber treatment, in the first instance normally by alkali, is of paramount importance for both of them to improve their interfacial adhesion with the matrix.

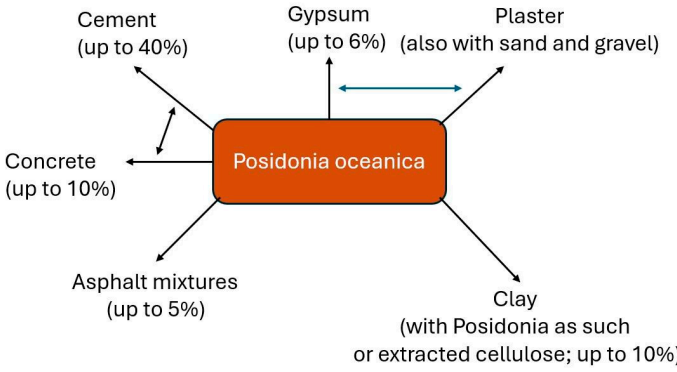


Figure 8. Application of Posidonia in cementitious composites, with indications of proposed amounts (original figure by the authors).

A possibility is obviously the integration of Posidonia in variable amounts into cement so as to modify its acoustic and thermal properties without compromising, and even possibly improving, its compressive strength. Initial data, provided by [83], indicated that the introduction of up to 40% Posidonia fibers reduced the compressive strength of cement by a factor of 4 at least, whereas flexural strength was more than halved, though with some benefit in terms of density, which decreased from 2.3 to 1.3. This was expected since the density of Posidonia fibers from egagropili was in the region of 0.35. On the other hand, 40% was probably an excessive proportion of fibers, and their lower criticality in flexural performance suggested rather exploiting, as detailed above, their acoustic and especially thermal conductivity by integrating them into the wall in small amounts.

This has been done with an amount of up to 20% Posidonia fibers in a cement produced with a water/cement ratio equal to 0.50 [84]. In this case, the maximum value of compressive strength of 33.60 MPa was obtained for the introduction of 10% Posidonia fibers from Tunisia [85]. An additional outcome also yielded a reduction in the sound transmission class, as defined in ASTM E413-87 standard [86], by over a dB. Another study found that the introduction of 20% Posidonia fibers into cement paste offered a decrease of 22% in terms of thermal conductivity, but even an increase in toughness amounting to 65% [87]. As regards plaster, the introduction of up to 20% Posidonia fibers into it offered a very large decrease in thermal conductivity from 0.35 to 0.11 $W*m^{-1}K^{-1}$, while reducing the thermal diffusivity from 3.18×10^{-7} to 2.05×10^{-7} m^2s^{-1}. In the process, the density of the material was also decreased by 35% [88]. To preserve compressive and flexural strength, though, the addition of 10% fibers in plaster was better suggested, and this material also has a sound absorption coefficient of 0.78 for a frequency range between 1000 and 4000 Hz [89]. In the specific case of Tunisian gypsum plaster, an optimization process for the composition was also proposed to achieve an absence of mixing loss and the highest mechanical properties at the same time; this indicated that the optimal ratio was Posidonia/(Plaster + Sand + Gravel) = 0.0321 [90]. The levels of addition of Posidonia

fibers recommended in the case of plaster are generally low, attaining in some cases a few percent, such as in [91] (6% Posidonia + 2% white pine), with substantial benefits for density (reduced by up to 30%), yet with a decrease in mechanical properties and modifications of fracture modes if these quantities are exceeded. The application of Posidonia fibers in low amounts (less than 5%) has also been performed in the case of addition to asphalt mixtures, which appears, therefore, to be a serious case for the downcycling of these filling materials [92]. Though being recognized as a potential improver for stiffness, the effect on water absorption and therefore drainage does not appear consistent with added quantity, which is possibly due to the dimensional variability of Posidonia short fibers.

Still preserving the concept of a maximum amount of Posidonia at 20%, results obtained on a clay-based material indicated that both the flexural and compressive strength performances were substantially preserved in that case, though the best performance was obtained with 10% Posidonia [93]. Furthermore, the introduction of fibers allowed an increase in the material porosity, which reached 52.4% with 20% fibers, together with a 0.17 $W*m^{-1}K^{-1}$ thermal conductivity. Given this particularly successful link between clay and Posidonia, a more complex development was offered by coupling the use of halloysite clay and cellulose extracted from Posidonia [94], on which further details are offered in a later part of this work (Section 4.1). Various mixtures of cellulose/halloysite clay nanofibers have been prepared, from 100/0 to 20/80, with the idea of proposing the formation of geopolymers obtained by aqueous casting. In a general sense, geopolymers have been considered an adapted host material for different types of waste [95], including sea-derived ones [96]. Other attempts in this sense proposed the production of Posidonia-reinforced geopolymers through the use of Posidonia mixed with other lignocellulosic material by dry mixing [97,98].

4. Processing of Posidonia Fibers for Composite Applications

4.1. General-Purpose Studies Evaluating Posidonia Fiber Potential in Polymer Matrices

For over a decade now, Posidonia has also been considered as a potential fiber for introduction into biocomposites. This is likely to represent a step forward in the upcycling of this natural waste with respect to what was reported above because, in that way, Posidonia would be used as a recognizable fiber with its own properties and for its specific composition, rather than a generic filler. As is frequently the case, the first attempts have been carried out using thermosetting matrices, such as epoxy or unsaturated polyester (UPR). A comparison of the flexural performance of composites with 20% Posidonia fibers demonstrates that the deflection of epoxy composites is around three times more important than that in the case of unsaturated polyester [99]. This indicated a water saturation for epoxy resin composites of over 10% compared with 4% for UPR.

In natural fiber polymer composites, the problem of water absorption is of paramount importance, also as a route for biofouling [100], while the potential to add Posidonia waste into a marine structure to possibly reduce it has also been recognized [101]. To predict the potential for application in real environments, a study on fire resistance of epoxy–Posidonia composites was conducted in [102], which demonstrated an extinguishing power of 52% over pure epoxy for an introduction of 12% Posidonia fibers.

The use of conventional thermoplastic as the matrix for Posidonia fibers has been limited so far though, possibly because it may appear unrelated to achieving higher sustainability. A study on polypropylene matrices reported that the combined effect of alkali and silane treatment is largely beneficial for tensile and flexural performance over untreated ones, though only the introduction of 20% Posidonia fibers really appeared advantageous, possibly due to the difficulty for these to properly settle into the 3–4 mm diameter granules for injection molding [103]. In the case of high-density polyethylene (HDPE), the

compatibilization of the matrix through the use of 3 wt.% of maleic anhydride allowed obtaining an increase in properties with up to 40% Posidonia fibers, in particular in the stiffness and the stabilized torque at 170 °C, to enable material processing [104]. Another study on 10 wt.% maleic anhydride-grafted polyethylene with an amount of 20% Posidonia fibers revealed that this level of compatibilizer would be effective in achieving a sound fiber–matrix interface, while applying a high concentration of chemical treatment (10% NaOH) would prove quite detrimental for the performance [105]. Yet actually, the most interesting study was performed with bio-based polyethylene and proved that up to 40% Posidonia fibers increased the properties of a bio-based (sugarcane-obtained) polyethylene matrix, increasing tensile and flexural stiffness and Shore D hardness. This occurred obviously at the expense of elongation, which decreased to 3.3 (±1.4)% due to the introduction of 40% fibers, which practically reduces the possible application of the material at this level of reinforcement, also due to the water absorption of 8% at saturation, which was instead maintained below 3% for 30% reinforcement [106]. On conventional (3% maleated) polyethylene, the limitations in the toughness of Posidonia appeared to have been overcome by the addition of another waste, such as deinking paper sludge (DES), through the fabrication of hybrids with the maximum amount of each of the fillers not exceeding 30% [107].

It is noteworthy though that these results are not comparable with what was obtained by the use of black spruce wood fibers, which evidenced the criticality of the Posidonia fiber process in conventional thermoplastics.

4.2. Use of Posidonia Fibers in Combination with Polysaccharide-Based Biodegradable Matrices

The principal activities for using Posidonia fibers in fully bio-based composites concern the use of poly(lactic acid) (PLA), which is obtained from corn starch raw matter. Despite most activities involving PLA being focused so far mainly on its use in packaging and for relatively low-duration products, the performance of PLA-based composites in the marine environment has also been investigated [108]. This has been done with the understanding that the diffusion of PLA as the most used polymer for additive manufacturing applications would span over many sectors, especially in view of the availability of high-molecular-weight grades of the material. In the long run, this would enhance the customization of the material for critical operations, such as repair, which are gradually diffusing also in the marine sector [109]. On the other hand, a number of works have been performed using cereal-derived matrices together with Posidonia fibers with the aim of improving the properties of bio-based packaging, namely using corn starch [110] and wheat gluten [50]. With this in mind, Posidonia has also been considered among other lignocellulosic particles for release studies aimed at food packaging applications [111].

Though this is not strictly linked with a potential marine application, it may be significant to note that thermoplastic starches (TPSs) may represent an alternative to PLA when the material is deemed to be 100% composed of biomass waste. Obviously, TPS properties are considerably inferior to PLA ones in most cases; despite this, the possibility of the easy blending of these two matrices offers potential for development, also in view of the introduction of further refuse materials, such as Posidonia fibers [112]. Some success was also obtained using very small Posidonia particles, milled and sieved and then extracted using hexane, dichloromethane, and acetone, with a size distribution centered around 50 microns, for the production of films of 500-micron thickness. The matrix employed was based on potato starch and a co-polyester, and hot pressing was used to introduce up to 30 wt.% of filler. In this way, even at this concentration, an elongation of 27.7% was preserved together with 18.2 MPa tensile strength and 180.5 MPa Young's modulus [113].

As regards works aimed at the more structural application of bio-based biodegradable matrices with Posidonia fibers, in [114], PLA composites were fabricated by compression molding at 190 °C, applying a 100-bar pressure for 3 min. The fibers, showing an internal porosity in the region of 74%, were ground to two different diameter distributions, with particles smaller than 150 microns and between 150 and 300 microns, respectively, and introduced in the matrix in amounts of 10 or 20 wt.%. The main limitation appearing was in the reduction in the strain at failure from 3.66% to 2.46% in the best case, leading to the premature failure of the materials. In contrast, the tensile and flexural stiffness of the matrix was increased in a proportion similar to that of the weight of fiber inserted. The introduction of a larger amount of Posidonia fibers, i.e., 30%, was possible in a poly(hydroxyalkanoate) (PHA) matrix, which was plasticized by the addition of 10 wt.% of poly(ethylene glycol) (PEG) [115]. In this case, starting from a matrix considerably softer than PLA, it was possible to obtain an increase in Young's modulus from 1.24 to 2.3 GPa, which was similarly reflected in an improvement of impact energy from 1.63 to 3.8 kJ/m^2.

4.3. Posidonia as a Source of Nanocrystalline Cellulose (NCC) for Nanocomposites

Extracting nanocrystalline cellulose (NCC) from lignocellulosic biomass is a procedure that offers exceptional properties and is especially suited to applications in the film format and in fields where absolute control over the variability in performance is needed. In practice, applications span from biomedical to packaging materials, or even to papermaking [116]. Conversely, NCC has also been perceived as a suitable route for the upcycling of biomass waste into high-performance materials, and therefore, the interest in NCC is definitely more general [117].

Posidonia oceanica fibers have also been considered as a viable candidate, even in spite of their partially lignified character, for the production of NCC. Recognizing this difficulty, in some cases, both a cellulosic crystalline fraction and a lignified one have been extracted to propose their combined use in a protein-based matrix, based on hemp seed oil [118]. Delignification and acid hydrolysis with hydrochloric acid and then neutralization by sodium hydroxide offered fibers with an average diameter of 8 microns and cellulose crystallinity approximately equal to 74% from Posidonia obtained from Algeria's Mediterranean coast [119]. A bleaching process, followed by a two-stage sulfuric acid hydrolysis, offered similar results, with aspect ratios (length/diameter) of around 40, with nanocellulose crystals showing the typical birefringence indicating their effective dispersion in the solution [120]. The yield obtained was around 14%, and the introduction of these fibers in a PLA matrix in a maximum proportion of 3% preserved the optical transparency of the polymer, together with some improvement in mechanical properties with controlled brittleness, when the fibers were modified with a surfactant [121].

Other works are based on pretreatment, following alkalization, aimed at nanocellulose fibril isolation through an oxidation process mediated by the 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) radical [122]. This method is typically coupled with a subsequent mechanical treatment by steam explosion [123]. A specific work was aimed at introducing the so-obtained NCC, which presents fibers with a higher aspect ratio, around 200 when extracted from Posidonia loose leaves and around 70 when derived instead from Posidonia balls, in a rubber matrix. In practice, the co-processing of leaves and balls would allow obtaining NCC with various aspect ratios, yet similar mechanical and thermal properties [124]. In particular, a latex of poly(styrene-co-butyl acrylate) was used, where up to 15% NCC was introduced. The geometry of the Posidonia-extracted NCC fibers was as a whole similar to those from many other species, which suggested possible further developments. The most substantial improvement in storage modulus was obtained when passing from 0

to 10% Posidonia NCC, where the value of E′ passed from less than 10^6 to above 10^8, with only limited advantage beyond that NCC content [125].

5. Opportunities and Future Directions

The exploration of the use of Posidonia balls and fibers is currently attracting some interest, and for the combined requirements of reducing the environmental footprint of composite production and the very large and steadily growing availability of secondary raw material, this is likely to continue. The literature indicates the presence of many studies exploring the right collocation of the fiber in a material context, as a standalone product in compacted boards, or in the field of cementitious or polymer composites. The principal gaps are nonetheless in the difficulty of assessing the environmental impact in comparison with composites with other fibers since Posidonia appears a sui generis filler with difficult extraction, variable geometry, and a tendency to agglomerate in resin, rather than distribute. A solution that has often been practiced is, therefore, their milling to low-aspect-ratio particles, if not solvent extraction. It is no surprise that nanocellulose extraction proved quite successful with Posidonia, in spite of their important lignin content (up to 34%). This approach towards nanomaterials has even led to the development of Posidonia particle hybrids with graphene nanoplatelets in a poly(lactic acid) (PLA) matrix, which appears rather a curiosity in the context of sea-derived refuse [126].

The situation appears slightly more promising in cementitious composites, where the low thermal properties of Posidonia fibers can be valued when compared with traditional insulating materials, and sound absorption properties also showed some merits. As far as polymer composites are concerned, it can be noticed that the drive towards switching to bio-based matrices tended to fade somehow over time, in the last two decades, also due to the difficulty of introducing a large amount of filler into them, as any waste-related work would suggest.

Another issue that has limited the use of secondary raw materials from Posidonia so far is the competing interests of the preservation of beaches, according to the previously discussed “ecological beach” model, which would suggest preserving stranded Posidonia whenever possible, and of the aforementioned use. The same concept of “litter” applied to these materials has often been discussed, preferring a definition of “sea-derived” materials [127]. However, the overwhelming amount of material available in regions such as the Mediterranean coast area, which cannot be left to become putrescent on the beach (not to say in harbor areas, where it becomes easily contaminated), indicates the continuing interest in this topic, which is ultimately the focus of this research.

For completeness, the investigation on the characteristics of Posidonia’s potential as a material is being currently performed in various other fields, such as for catalytic materials [128], in the development of lithium–sulfur batteries [129], or, e.g., as a biotechnological source for enhancing the production of melanin by specific bacteria [130]. Further applications might be even suggested from the various functions Posidonia has underwater, such as for iridescent light modulators, therefore taking a stand on a possible biomimetic inspiration, which might also offer some suggestions for future research [131].

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