Recycling of Beached Posidonia Oceanica in the Construction Sector

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Abstract. The paper aims to outline the state-of-the-art related to the possible reuse of the Posidonia Oceanica in the construction sector. The Posidonia Oceanica constitutes an important resource from the point of view of the protection of the marine environment, however the coastal deposits of Posidonia Oceanica, caused by the modification of the sea currents due to the construction of coastal infrastructures, constitute a serious problem for management and tourist perspective. The paper takes stock of the European and Italian regulatory framework and analyzes the results of the studies present in the literature concerning the treatments Posidonia Oceanica should undergo before its reuse in the construction sector, the construction products in which it can be used and the physical-mechanical performance of these products.

Keywords: Posidonia Oceanica · Construction Sector · Recycling

1 Introduction

The Posidonia Oceanica (PO) is a plant that produces flowers and fruits and in optimal conditions colonizes huge portions of the seabed called meadows [1]. The PO meadows represent biocenosis very complex and very well structured that are typical of the Mediterranean Sea. They are characterized by a very high biological variety of species and represent nursery areas for juvenile fish as well as a refuge for many fish. In addition to having this role of protecting biodiversity, the PO meadows provide important ecosystem services: they absorb carbon dioxide, produce oxygen, stabilize the seabed through the rhizomes and therefore protect the coasts from coastal and seabed erosion [2]. The PO meadows are subject to natural exfoliation, the leaves darken and fall and go either towards the open sea forming mulching areas as in the woods, or on the ground forming coastal deposits. In the natural coastal dynamics, winter coastal storms should throw the PO coastal deposits back into the sea, but anthropic works in the coastal areas (constructions of quays, ports, etc.) blocked this natural dynamic [3, 4]. Therefore, huge quantities of PO are deposited along the coasts, with negative consequences to beach qualities, especially in tourist areas. Thus, an invaluable resource for the environment becomes a problem for economic and tourist development. Figures 1 and 2 show PO meadows, beached PO balls and beached PO leaves.

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Fig. 1. PO meadows and beached PO balls.



Fig. 2. Beached PO leaves.

The management of PO coastal deposits is complex as they are protected by various regulations, and it is not clear whether they are to be considered waste or resources.

At European level, the Barcelona Convention and Amendments [5], the Council Directive 92/43/EEC [6], and the Marine Strategy Framework Directive [7] establish a framework for community action in the field of marine environmental policy.

The legislative framework in Italy is not yet complete and does not appear to be in line with that of the European Community. The Italian Consolidated Act on Environment [8] classifies waste lying on lake shores and on the banks of watercourses as urban waste. The Italian Legislation [9] allows the burying in situ of PO and jellyfish deposited in the beach from the coastal storm without transport. The Italian Law called "Save the Sea" [10], declares that PO coastal deposits could be treated for re-use in other sectors.

In the last ten years, applied research has found interesting solutions for the valorization of PO [11–27]. The PO usage as energy source is difficult due to its low combustible behavior under fire [28], although research is underway on the use of PO as biomass source, e.g. for anaerobic digestion [29], but it can be used as a component of building elements having suitable fire resistance and thermal and mechanical behavior.

At European level, two research projects have been developed aimed at the management of beached PO and its reuse as recycled material. The first is the SEA-MATTER project [30], which aimed to demonstrate the technological and economic feasibility of using coastal algae and seaweed accumulations as raw materials in the composites industry. The goal was to use wet-laid nonwoven textile technology to turn this marine biomass into composite products, in the first instance acoustic panels for buildings. The second is the LIFE REUSING POSIDONIA project [31], which aimed to implement and evaluate alternative construction techniques for a building complex prioritizing the most ecological locally sourced products and demonstrating their economic viability. Specifically, beached Posidonia packed in re-used pallets as insulation material.

In this frame, this paper aims to review the state-of-the-art relating to the use of PO in the construction sector, highlighting the treatments that the material can undergo before being used, the products that have been manufactured so far and the main physical-mechanical performances of such products.

2 Regulatory Framework and Case Studies

The Barcelona Convention and Amendments [5] form the legal framework of the Mediterranean Action Plan (approved in 1975), developed under the United Nations Environment Programme (UNEP) Regional Seas Programme. The key goal of the convention is to "*reduce pollution in the Mediterranean Sea and protect and improve the marine environment in the area, thereby contributing to its sustainable development*".

The Council Directive 92/43/EEC [6] identifies natural habitat types of community interest whose conservation requires the designation of special areas. According to the habitats hierarchical classification of [32], PO beds are priority habitat types.

The development and implementation of the Marine Strategy Framework Directive [7] should be aimed at the conservation of marine ecosystems. This approach should include protected areas and should address all human activities that have an impact on the marine environment.

The Italian Consolidated Act on Environment [8] classifies waste lying on lake shores and the banks of watercourses as urban waste. This classification is not expected in the European regulatory framework, but it is useful to identify the management authority.

The Italian Legislation [9] declare that "*Without prejudice to the regulations on the protection of the marine environment and the provisions on the subject of by-products, where there are unequivocal elements which suggest that their presence on the shoreline is directly dependent on storm surges or other natural causes, it is permitted to bury the Posidonia and beached jellyfish, provided that this takes place without transport or treatment*".

The Italian Legislation [33] allows the use of beached PO to produce fertilizers, after the separation of the organic fraction from the sand.

The Italian Legislation [34] is a specific law that aims to classify the materials to be treated and to define their management.

The Italian Law [10] declares that "*In cases where the previous options relating to on-site maintenance or reintroduction into the natural habitat are not possible, these residues are sent to waste management plants, which, using washing technology, allow*

the effective separation of the sandy component from the vegetable fraction, as well as the separation of man-made waste. The washed sand recovered in the above washing plants is primarily intended for relocation to the original beach. The washed vegetable fraction recovered in the washing plants mentioned above, like other organic material, can be usefully used to produce soil improver in composting plants or valued for re-use in other sectors".

In the light of the Italian regulatory framework, two important interventions were carried out in Italy aimed at the recovery and reuse of beached PO. The two case studies are explained in the following sections.

2.1 Case Study Respect Your Capital in Marina Di Cecina Tirreno Sea, Italy (2020)

The interventions in Marina di Cecina (Livorno), on the Gorette beach [35], were conceived by Marevivo Onlus and Pramerica SGR with a twofold objective:

1. support the Municipality of Cecina in the operations of cleaning the coast from beached PO, adopting an experimental protocol capable of reducing environmental costs,
2. maintain and document the PO meadow in front of the beach beneficiary of the intervention.

A demonstrative protocol has been implemented in which the PO, once removed from the beach, was transformed into compost, and the recovered sand was relocated to the Gorette beach, thus safeguarding the seabed.

The cost-benefit analysis of the intervention clearly showed that the RESPECT YOUR CAPITAL protocol manages to reduce the environmental costs of the PO removal operations, guaranteeing a social rate of return of 14.2%. This value, which indicates the increase in social welfare induced by the protocol, is particularly high if compared to the reference rate proposed by the European Union and implemented by Italy, which is 3.5%.

The adopted protocol demonstrated that removal costs appear to be slightly lower than those currently in use, and specific parameters able to conduct in-depth analyses in support of marine policy are needed.

It should be noted that, due to Italian regulatory framework, once treated, PO cannot be reused for the formation of dunes to be placed on the beach. Having this possibility would be of great ecological and social importance.

Following the results of the project, the Municipality of Cecina offered an area for the location of a plant for the recovery of beached PO.

The RESPECT YOUR CAPITAL protocol allowed 585 tons of surface layer of the beach to be removed with a system that did not include the presence of weighed vehicles and therefore respectful of the environment. About 150 tons of beached PO were recovered and separated from 320 tons of sand, which was purified from anthropic material (plastics and waste in general, for a total of about 15 tons which were correctly disposed of) and then brought back to the beach, thus reducing the effects of coastal erosion.

2.2 Case Study Beached PO: From Problem to Resource in Port of Sperlonga, Tirreno Sea, Italy (2021)

The Port of Sperlonga (Latina) is inserted in a high-quality environmental context, where the presence of stable and dense meadows of PO is documented. PO deposits are recurrent throughout the stretch coast close to the port area and are transported inland of the port basin itself from storm surges and currents. The sediment to be moved is under a layer of organic debris, about 30–50 cm thick, which appears to be mainly made up of submerged banquettes of PO leaves.

The purpose of the case study [36] was to examine the possible activities to be carried out to deal with the situation in a sustainable way, taking into account the current legislation. The study highlighted the following possibilities for PO treatment:

- disposal in an authorized landfill,
- extraction of active ingredients for medical applications or phytocosmetics,
- production of insulating products, especially for roofs and floors, thanks to PO thermal insulating properties and fire resistance,
- production of biocomposites, natural products obtained coupling different raw materials, to obtain eco-sustainable final products with excellent performance,
- deliver the organic material to recycling plants as input matrix to composting or anaerobic digestion plants for the production of soil improvers.

The case study pointed out that it is advisable to plan a pilot study aimed at achieving the overall feasibility assessment of the interventions and the cost-benefit estimate on the basis of experimental results aimed at defining suitable local contexts, management methodologies, technologies and specific skills that can be structured into production systems and circular economy supply chains.

3 PO Reuse in the Construction Sector

The review of the state-of-the-art relating to the use of PO in the construction sector pointed out that, after proper treatments, PO might be valorised as insulating and reinforcement material in buildings thanks to its positive influence on the physical and mechanical properties of the composites it becomes part of.

3.1 PO Treatments

The analysis of the state of the art concerning PO treatments highlighted several preliminary treatments the collected beached PO goes through before its use as recycled material in the construction sector.

Table 1 reports the main treatments proposed in scientific literature references along with the building product manufactured with recycled PO.

3.2 Mechanical and Thermophysical Characterization of Realized Products

Based on scientific literature references, in Table 2 the main tests carried out on realized products are reported.

Table 1. Main treatments planned for PO and manufactured products.

Ref	Treat	Description	Product
[20]	1°	Milling process using an industrial mill to convert PO and balls PO into short fibres	Fibrous material with high cellulose content. The polymeric matrix to bind the PO fibres was wheat gluten. Composites were made by hot-press moulding by varying the gluten content on composites in the 10–40 wt% range
	2°	Washing stage of short fibres with distilled water, until clean wastewater, to remove sand, soil, and other wastes	
	3°	NaOH (10 wt% in water) treatment for 24 h to remove excessive impurities from the surface of the fibers and made fiber swollen	
	4°	Drying process at 60 °C for 24 h of soaked fibers	
[21]	1°	Cleaning PO in fresh water to remove salt particles and other organic and inorganic debris, which were also manually removed	Polyurethane polymer matrices: resin, treated PO, and pine wood particle for interior lining constructive elements. The resin was poured into the wood-PO mixture, and the mix was stirred by hand until a homogeneous consistency was achieved
	2°	Drying process at 110 °C in an electric oven for 2 h	
	3°	Crushing mechanically to a 1 mm maximum particle size using a cutting mill	
	4°	Sieving to remove all particles lower than 0.3 mm to optimize the particle-resin mixing process, because due to the large specific surface area most of the polymer would be absorbed and the mixture wouldn't be homogeneous	
[22]	1°	Washing and drying under normal conditions (temperature: 20 °C ± 5 °C, humidity: 60% ± 5%)	Ecological loose-fill insulation material to use in the building field
	2°	Soaking in sodium hydroxide solution under different conditions. First treatment T1 consists in emerging fibers in a 2% NaOH solution during 2 h at 80 °C. Second treatment T2 is carried out using 0.75% NaOH solution for 1 h at 100 °C. Last treatment T3 consists in reproducing the T1 treatment to the fibers already treated with this same treatment	

(*continued*)

Table 1. (*continued*)

Ref	Treat	Description	Product
[23]	1°	Preliminarily treated with tap water to remove salt crystals: an amount of 500 g of PO leaves were weighed and shoved into a 10 l glass vessel. The flow of the tap water was kept at 5.7 l/h, which led to a residence time for the water of circa 105 min	Production of alternative building material in the form of pressed panels
	2°	Valuating salt concentrations using a conductivity meter and the respective calibration curve for salt concentrations	
	3°	Repeating 1° treatment until the conductivity of the outlet water reached the values of the tap water	
	4°	Drying naturally for 24 h	
[24]	1°	Washing with water to remove sand and other impurities	Mixtures composed of plaster and fibers of PO to manufacture an insulating and ecological material
	2°	Drying in an oven at a temperature of 30 °C for 48 h	
	3°	Storing under normal conditions (temperature: 20 °C ± 5 °C, relative humidity RH: 60% ± 5%)	
[25]	1°	Washing and rinsing with distilled water to eliminate sand and other contaminations	Manufacturing of particle boards from beached PO
	2°	Drying at room temperature for about two months	
	3°	Drying at 105 °C to 6.5–7% moisture content	
[26]	1°	Cleaning from sand and debris	PO fibres added to lime mortars to improve their characteristics
	2°	Placing in an air-conditioned room of stable conditions (20 ± 2 °C, 65 ± 3% RH), to attain mean equilibrium moisture content (11.13%)	
	3°	Mechanically crushing into smaller particles in the form of fibres (5–10 mm)	
	4°	Hydrothermal treatment at 140 °C, in an atmosphere saturated with steam, at a pressure of 1.5 atm for 2 h	

(*continued*)

Table 1. (*continued*)

Ref	Treat	Description	Product
	5°	Cooling down in desiccators and afterwards weighed and stored in a climate-controlled room, at 20 ± 2 °C temperature and 65 ± 3% relative humidity	
[27]	1°	Washing	Cement paste reinforced with PO fibers
	2°	Drying	
	3°	Crushing	

Table 2. Tests carried out on realized products.

Ref	Tests
[20]	Standardized flexural tests for evaluating mechanical properties Thermo-mechanical behavior of composites evaluated with dynamic mechanical analysis and determination of heat deflection temperature
[21]	Density, compressive strength, elastic modulus
[22]	Thermal conductivity and diffusivity of samples measured with the Hot-Disk method, and density
[23]	Density, flexural tests, water absorption and swelling properties
[24]	Compressive strength, flexural strength, thermal conductivity, and thermal diffusivity
[25]	Internal bond strength, modulus of rupture and modulus of elasticity, resistance to axial withdrawal of screws and thickness swelling after 24 h and 48 h immersion in water
[26]	Mechanical properties of PO fibres, chemical characterization of fibres, microstructure using scanning electron microscopy, fresh state properties of lime mortars, harden state properties of lime mortars
[27]	Thermal conductivity and thermal diffusivity are measured with the Hot-Disk Transient Plane Source. Density, tensile and compressive strength, and fracture toughness of composite

3.3 Results and Discussions

PO Treatments

In most cases, the treatments are simple and consist of washing, drying, crushing, and sieving. In some cases, to improve the durability of the PO fibres in the alkaline environment of lime/cement mortar and to remove salt crystals (mainly NaCl), PO could be preliminarily soaked in sodium hydroxide solution (solution at 2–6%).

However, their extraction and preparation did not need high technicality.

Mechanical and Thermophysical Characterization of Realized Products
The results obtained from the studies present in the scientific literature are summarized in Table 3.

Table 3. Results from scientific literature.

Ref	Product/composition	Characteristics
[20]	3mm composite sheets PO + wheat gluten protein binder	Flexural strength 22.2–40.8 MPa Flexural modulus 2.35–3.99 GPa Impact energy 0.10–0.11 kJ/m^2
[21]	max 10mm panels PO + pine wood particles + polymer matrice (PU or MDI)	Density 0.629–1.110 g/cm3 Compressive strength 0.99–9.45 MPa Elastic modulus 308.1–1240.9 MPa
[22]	Loose-fill material	Density 17–155 kg/m^3 Thermal conductivity 0.043–0.070 W/mK Thermal diffusivity 0.30–1.06 × 10^{-6} m^2/s Heat capacity 2169–2533 J/KgK
[23]	Composite boards PO leaves + PMDI binder + acetone	Density 308–480 kg/m^3 Flexural strength 2.67–7.94 MPa
[24]	40 × 40 × 160 mm^3 and 270 × 270 × 40 mm^3 specimens PO fibers + Hemi-hydrate gypsum plaster	Density 1.11–0.66 g/cm^3 Flexural strength 4.5–7 MPa Compressive strength 13.8–14.8 MPa Thermal Conductivity 0.11–0.29 W/mK Thermal Diffusivity 2.05–2.9 × 10^{-7} m^2/s
[25]	16 mm single layer particleboards PO leaves + wood chips + urea-formaldehyde resin	Density 0.53–0.55 kg/m^3 Modulus of rupture 1.26–2.83 MPa Modulus of elasticity 279.23–583.29 MPa Internal bond strength 0.03–0.12 MPa Moisture content 9.93–11.41% Thickness swelling 57.42–66.70%
[26]	40 × 40 × 160 mm^3 specimens PO fibres (hydrothermal/alkaline treatment) + lime mortar	Flexural Strength 0.375–0.894 MPa Compressive Strength 0.745–1365 MPa Dynamic modulus of elasticity 3590–7450 MPa Open porosity 33.88–35.09%
[27]	40 × 40 × 160 mm^3 and 44 × 44 × 10 mm^3 specimens PO fibers + Portland cement paste	Density 1613–1761 kg/m^3 Thermal conductivity 0.559–0.718 W/mK Thermal diffusivity 0.298–0.362 × 10^{-6} m^2/s Flexural strength 4.2–4.8 MPa Compressive strength 23–29 MPa

Composites based on PO waste and 10–40 wt% wheat gluten protein as binder [20] show interesting mechanical performance, like some commodity plastics such as polypropylene. Natural fibers are highly hydrophilic, thus composites with natural fibers are highly sensitive to moisture and water uptake. As PO fiber is mainly composed of cellulose and hemicellulose, its sensitivity to water is higher than gluten, so that as the total amount of gluten increases, the water uptake is reduced.

Panels made of a mixture of PO fibers and pine wood particles with two different polymeric matrices (PU-823 – monocomponent PU, and PU-815 – bicomponent PU with MDI isocyanates) as binder [21] show that, in comparison to standard wood particle boards, the mechanical performances do not reach European standards requirements. However, particle boards made of 75% PO and 25% wood particles, and a 20–30% by fibres mass MDI matrix showed the best strength and stiffness to density ratios, being the stiffness even similar to that of a panel made totally in wood and MDI in the same dosage.

The chemical sodium hydroxide (NaOH) treatment can be needed to remove impurities from the fiber's surface [22]. The treatment does not change noticeably the thermal conductivity, the thermal diffusivity, and the heat capacity of PO fibres, which are comparable to those of industrial insulation materials. Therefore, PO fibres could be a promising ecological loose-fill insulation material in the building field.

When PO leaves are bound with polymeric methylene diphenyl diisocyanate (MDPI) to produce leaf boards [23], good flexural strength can be reached, and swelling test results indicate a moisture high resistance. Therefore, it is not suitable to commit PO waste in the landfill, but it could be beneficial to use this biomass in construction.

PO fibres bound with semi-hydrate β plaster realize a plaster with suitable mechanical and thermophysical properties [24]. The addition of PO fibers improves the compressive and flexural strengths and the thermal insulation of the new material.

Particleboards from PO fibres (50%) and wood chips (50%) bound with urea-formaldehyde resin have good performances related to swelling [25].

The use of PO fibres in lime composites improves fresh state (air content, water retention, workable life) and mechanical properties (flexural and compressive strength) [26]. The treatment of PO leaves, both in the presence of NaOH or CaOH, improves the adhesion of the fibres to the lime matrix. In particular, the mechanical properties of the composite were improved by 60% when PO fibres were treated with NaOH.

The reinforcement of cement paste with PO fibers produces the improvement of material insulation properties and compressive and flexural strengths in comparison with cement paste without PO fibres [27]. Incorporating PO fibres in cementitious matrix significantly increases the material ductility and its ability to bridge cracks.

The analysis of the state-of-the-art highlights that the PO can find various uses in the building sector. The research conducted so far is still non-organic, however it highlights the potential of PO as a usable material for the production of composites characterized by increased physical-mechanical properties. Moreover, the ISPRA (Italian Institute for Environmental Protection and Research) report [37] expresses that the accumulations of beached PO on the Italian coasts vary in the range 20 t/year-90 t/year, making clear the economic sustainability of the use of PO in the construction sector.

On the other hand, the analysis of the European and Italian regulatory framework highlights the need for the legislator to definitively clarify that PO beached for natural causes does not constitute waste if treated on site as a natural mass reintroduced into the habitat, or if used as a natural raw material for production purposes, inserting the recovered PO in a circular economy perspective.

Researchers and far-sighted entrepreneurs have focused on the problem of reconciling environmental protection and tourist use of beaches, implementing good practices to transform the problem of managing coastal areas subject to PO accumulation into a series of activities which, on the one hand allow the coast to be preserved (recovery of sand, removal of plastic and waste), and on the other the recycling of PO in other productive sectors such as construction one.

The Italian case studies RESPECT YOUR CAPITAL [35] and BEACHED PO FROM PROBLEM TO RESOURCE [36] and the Spanish projects SEA-MATTER [30] and LIFE REUSING POSEIDONIA [31] are important examples to replicate.

4 Conclusions

The present paper addresses the problem of managing beached Posidonia Oceanica, which affects many areas of the Mediterranean basin, and the transformation of this material from waste to resource through its possible reuse in the construction sector.

To this end, the paper analyzed the state-of-the-art relating to the use of PO as a material for the construction sector, the European and Italian regulatory framework relating to the treatment and reuse of PO, and some case studies to be considered good practices for the management of the problem of beached PO accumulation through its reuse in construction.

The study highlighted the opportunities offered by the reuse of beached PO in the building sector and the need to intervene at a regulatory level to encourage this conversion.

Despite the research conducted so far is still non-organic, the analysis of the state-of-the-art highlighted that PO can be valorized as a building material for the manufacturing of composites characterized by increased physical-mechanical properties. However, for PO recycling and reuse in the construction sector to be followed, it is necessary that the legislation in force in Italy and in Europe classifies PO beached for natural causes not as waste but as natural row material reusable in the context of circular economy.

The possibility of using beached PO in the construction sector constitutes an opportunity to reconcile the need to protect the coastal environment with that of its tourist valorization. This is important especially for the development of territories such as islands, often structurally disadvantaged, for which the implementation of circular economies is beneficial and desirable.

This paper analyzed only the state-of-the-art related to the possible use of PO in the construction sector. Based on the collected data, future research developments aim to carry out experimental activities of beached PO recycling and reuse in buildings on the island of Sardinia (Italy), strongly affected by the presence of PO banquettes.

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