

Review

Posidonia oceanica Ashore Waste Biomass: State-of-the-Art and Valorisation Perspectives Within the Circular Economy Framework

Manuel Hernández-Escaño ¹, Rafael Borja ¹ , José Carlos García-Gómez ^{2,3}  and Francisco Raposo ^{1,*}

¹ Instituto de la Grasa-Consejo Superior de Investigaciones Científicas (IG-CSIC), Campus Universidad Pablo de Olavide, Carretera de Utrera Km 1, Edificio 46, 41013 Sevilla, Spain; mherandez@ig.csic.es (M.H.-E.); rborja@ig.csic.es (R.B.)

² Laboratorio de Biología Marina, Área de Investigación Biológica I + D + I del Acuario de Sevilla, Departamento de Zoología, Facultad de Biología, Universidad de Sevilla, 41004 Sevilla, Spain; jcgarcia@us.es

³ Estación de Biología Marina del Estrecho, 51001 Ceuta, Spain

* Correspondence: fraposo@ig.csic.es

Abstract

The accumulation of dead leaves from the Mediterranean seagrass *Posidonia oceanica* on beaches is a natural process that results in the formation of banquettes and, in some areas, spherical debris known as aegagropiles. These structures provide essential ecosystem functions, particularly coastal protection against erosion. Despite their ecological importance, accumulated *Posidonia oceanica* biomass is often perceived as undesirable waste by stakeholders such as beach managers, local authorities, and tourists, leading to its systematic removal. This review summarises the chemical characteristics of this marine biomass and assesses its environmental and socioeconomic impact. Additionally, some different valorisation pathways for this biomass waste are examined, including animal feeding, bioactive compound extraction, development of biochar, biofertilisers, and compost, production of biosorbents, biocomposites and building materials, and also energy generation. The findings highlight the significant potential of *P. oceanica* residues within circular economy strategies and underscore the need for improved management practices that recognise their ecological value.

Keywords: biomass; *Posidonia oceanica*; residue; valorisation; waste

1. Introduction

Posidonia oceanica (L.) Delile is a marine phanerogam of the Mediterranean Sea. It is the sole representative of the genus *Posidonia* within the family Posidoniaceae and belongs to the class Monocotyledoneae [1–3]. Among marine plants, it is the most abundant marine plant species in the Mediterranean basin, covering approximately 40,000 km² of the seabed [4–6]. It forms extensive, dense underwater meadows (Figure 1), ranging from shallow areas to depths of up to 40 m [7], and it constitutes a highly relevant ecosystem, hosting nearly a quarter of the region's biodiversity [8,9].

Posidonia oceanica (*P.o.*) meadows represent a key component of Mediterranean coastal ecosystems, performing crucial ecological and physical functions. These meadows contribute to water oxygenation, protect sandy coasts from erosion, facilitate dune formation, act as natural barriers that reduce sediment resuspension, and decrease the impact of currents and waves on the seabed by up to 75%, thereby enhancing coastline stability and mitigating hydrodynamic forces [7,11,12].



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Figure 1. Underwater meadow of *Posidonia oceanica* (L.). Source: Frédéric Ducarme [CC BY-SA 4.0] (Wikimedia Commons) [10].

It is important to note that in this review document, the terms beach-cast, banquettes, residue, and waste are considered as synonyms of *P.o.* lignocellulosic biomass.

2. Morphological Characteristics of *Posidonia oceanica* (*P.o.*)

The morphology of *P.o.* includes a creeping stem or rhizome, firmly anchored to the substrate, from which shoots bearing from four to eight dark green leaves emerge, reaching lengths of approximately 1 m. Rhizomes are arranged both horizontally and vertically, allowing the plant to expand and consolidate the meadow over the seabed. Horizontally growing rhizomes are referred to as plagiotropic rhizomes, enabling substrate colonisation. Vertically growing rhizomes, termed orthotropic rhizomes, help resist burial by sediments [11].

These rhizomes, together with living and dead roots, form the base of the meadows known as the *matte*, a structure in which the spaces between them are filled with sediments. Over time, the accumulation of these sediments and the vertical growth of orthotropic rhizomes gradually elevate the *matte* and consequently modify the seabed height [11].

The processes of growth, deposition, and biomass degradation in *P.o.* occur seasonally and annually, spanning several months to years [13]. This perennial marine plant exhibits a continuous foliar growth cycle, with leaf shedding in autumn and regeneration during winter [14]. Fallen leaves are cyclically incorporated into coastal ecosystems: some remain in the sea, participating in the food chain and sedimentation processes, while others accumulate along the shoreline [15].

Within a single year, *P.o.* meadows produce large amounts of residues such as leaves (blades and sheaths), rhizomes, and roots, which may contribute to biological sediment on the seabed and eventually degrade through the action of macroorganisms, microorganisms, and abiotic factors [3,13]. When leaves lose functionality, they turn brown and eventually detach, being transported to the coast, where they accumulate, forming structures known as “banquettes” (Figure 2) [16]. These formations, ranging from a few centimetres to several metres in thickness, are not composed exclusively of plant material and can contain up to 100 kg·m^{−3} of sediments, thereby contributing to the beach sediment balance [14]. This process occurs at higher rates in autumn, when sunlight penetration decreases, and strong storms are frequent [3,17]. In addition to their ecological importance, banquettes play a role in coastal protection by reducing erosion rates [13].

These plant residues, mainly fibres, can aggregate around a rhizome core and, as they consolidate with mineral particles and undergo progressive erosion, form ball-shaped structures known as *aegagropiles* (Figure 3), which are commonly found along Mediterranean beaches [17].



Figure 2. Accumulation of *P.o.* banquettes in Santa Margalida, Spain. Source: Ryan Hodnett [CC BY-SA 4.0] (Wikimedia Commons) [18].

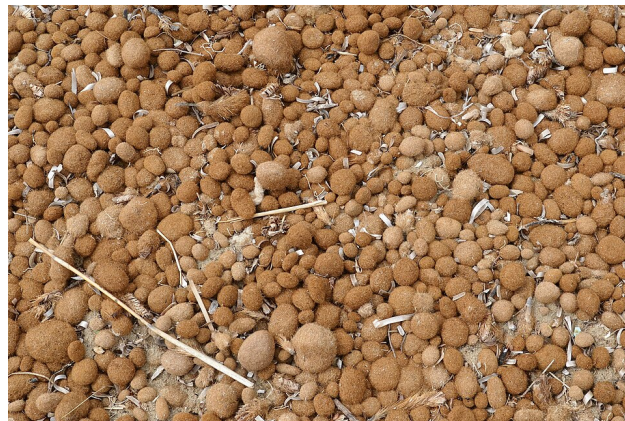


Figure 3. Accumulation of *P.o.* aegagropiles in Santa Margalida, Spain. Source: Ryan Hodnett [CC BY-SA 4.0] (Wikimedia Commons) [19].

Initially, fibres and sand aggregate and grow, fragmenting into smaller units through mechanical and/or microbial degradation until a sphere is formed [3]. These residues decompose slowly over several years and integrate with sediments, ranging in size from millimetres to several centimetres and potentially covering large areas. Eventually, they are transported to the shore by storms, at which point biotic degradation ceases due to desiccation [13,17].

Both the biomass-forming banquettes and aegagropiles can be partially degraded by bacteria and microfungi in the supralittoral zone before being consumed by detritivorous crustaceans, which complete digestion with the aid of their own enzymes and symbiotic microorganisms present in their hepatopancreas, releasing nutrients that can be utilised by other organisms [20].

3. Distribution of *P.o.* in the Mediterranean Area

Some studies estimate that *P.o.* meadows cover approximately 1–2% of the Mediterranean seabed, corresponding to a total area of about 1,224,707 hectares, and are present in 16 Mediterranean countries (Figure 4) [7,12,21]. These meadows typically occur at depths of up to 40 metres, and *P.o.* photosynthesis depends directly on sunlight availability, making water transparency a key factor for its distribution [22]. Meadow architecture can vary, ranging from continuous seabed cover to patches of different shapes, such as strips parallel to the shoreline or cordons perpendicular to it [3,7,12]. *P.o.* meadows are essential coastal ecosystems but have experienced widespread regression over the past decades due to human pressures and climate change, highlighting the need for mapping their distribution and monitoring their conservation status [3,12,22]. The study conducted by Marbà and

Duarte [23] concluded that *P.o.* meadows are highly vulnerable to warming, with substantial declines in shoot abundance, indicating that climate change poses a significant threat to this important habitat. Furthermore, according to Telesca et al. [21], the cumulative decline of meadows over the past 50 years is estimated at approximately 34%, suggesting that the combined effects of multiple local stressors primarily drive this widespread loss.

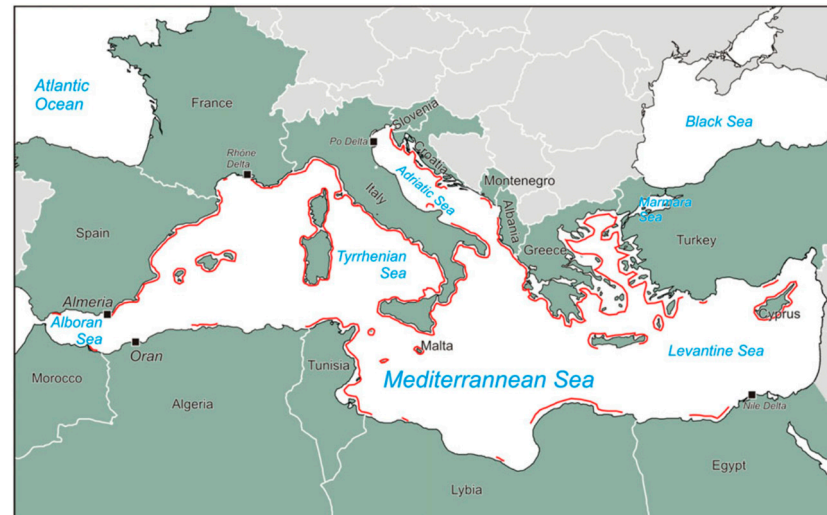


Figure 4. Geographical distribution of *P.o.* meadows across the Mediterranean Sea [12].

In Spain, the distribution of *P.o.* extends from Portbou, Girona (Catalonia), to Punta Chullera, Málaga, (Andalusia) [24]. Extensive and well-established meadows can be found in areas such as the Cabo de Gata-Níjar Natural Park in Almería, Andalusia, where some of the species' most pristine habitats are preserved. In the Balearic Islands, meadows cover a total area of 553.68 km², making this archipelago one of the regions with the highest concentration of *P.o.* in the Mediterranean [25]. In the Valencian Community, meadows have been mapped over 346.7 km² [21], while other regions, including Murcia and Catalonia, also host significant meadows, though of smaller extent. Collectively, these areas represent a strategic resource for marine biodiversity and contribute to the fulfilment of coastal habitat conservation objectives under the EU Habitats Directive.

4. Chemical Composition of *P.o.*

4.1. Proximate Composition

P.o. waste, typically collected as beach-cast biomass, shows characteristic moisture, organic matter, and inorganic matter fractions that reflect both its plant origin and its marine environment. The material generally exhibits moisture values in the range of 16–71% [26–29].

Volatile matter is high, generally between 56.76 and 67.50% [26,30], which is characteristic of plant-derived biomasses and contributes to rapid ignition and efficient devolatilisation during thermal conversion.

One of the most distinctive features of *P.o.* waste is its elevated ash content, commonly spanning 12–30.6% and reaching higher values in beach-cast material contaminated with sand, salts, or carbonates. This ash fraction contains inorganic compounds typical of marine-derived residues, including calcium, magnesium, sodium, and silica. This relatively high mineral load may influence combustion behaviour, slagging tendencies, and the overall energy yield [15,26,27,30–33].

To summarise, the proximate profile shows that *P.o.* waste is a high-volatility, medium-energy biomass with notable ash levels.

4.2. Ultimate Analysis

Overall, the elemental profile positions *P.o.* waste as a moderately carbon-rich biomass with low sulphur and nitrogen content but elevated mineral presence relative to terrestrial plants (Table 1). Ultimate analysis of *P.o.* waste shows carbon concentrations ranging from 31.80 to 44.60% [26,27,29,30,32,34], which are comparable to those of plant-derived residues. This characteristic supports its potential for energy conversion. Hydrogen content generally ranges from 3.35 to 6.44% [26,29,30,32], while nitrogen levels remain relatively low, typically from 0.17 to 5.70% [15,26,29,30,32,34], indicating a biomass with limited protein fractions and low potential for nitrogen-related emissions during combustion. Sulphur content is commonly very low at around 0.6–3.78% [26,29,30,32,33], which is advantageous for reducing SO_x formation in thermal processes. Oxygen constitutes the remaining fraction (34.66–60.44%), consistent with typical plant-based residues [26,27,29,30,32].

Table 1. Ultimate analysis of *Posidonia oceanica* biomass reported in different studies.

Refer.	<i>P.o.</i> Source	Carbon (%)	Hydrogen (%)	Sulphur (%)	Nitrogen (%)	Oxygen (%)
[15]	Bari (Italy)	-	-	-	5.70	-
[26]	Istrian peninsula (Croatia)	31.80	4.43	1.25	2.08	60.44
[27]	Kefalonia (Greece)	40.30	-	-	-	42.50
[29]	Chott Meriem (Tunisia)	42.10	6.44	3.78	1.52	34.66
[30]	Vada (Italy)	44.60	5.50	0.60	0.30	36.40
[32]	Northern coast of Tunisia	35.12	3.35	1.19	0.17	46.19
[33]	Monastir (Tunisia)	-	-	1.92	-	-
[34]	Alicante (Spain)	42.90	-	-	0.28	-

The corresponding heating values place *P.o.* waste in the medium-energy class, with higher heating values (HHV) between 11 and 18 MJ·kg⁻¹ and lower heating values (LHV) between 9.6 and 14.5 MJ·kg⁻¹ [26,30–32].

4.3. pH, Salinity, and Electric Conductivity

Beach-cast *P.o.* waste exhibits complementary chemical properties due to its marine origin and prolonged exposure to seawater. The pH of the biomass typically falls within a slightly alkaline range, often from 7.31 to 8.3, reflecting the presence of carbonate-rich inorganic material and residual seawater minerals [15,26–28,31]. Salinity levels in untreated residues are generally high, as the biomass can retain significant amounts of soluble salts, including sodium, chloride, and magnesium. This high value commonly indicates strong marine contamination, though it decreases substantially after washing or rainfall leaching. Consequently, the electrical conductivity (EC) of *P.o.* waste is elevated, indicating a high concentration of dissolved ions; EC values often classify the material as highly conductive compared with terrestrial plant residues. Together, these parameters underscore the influence of the marine environment on the chemical profile of *P.o.* waste and highlight the importance of desalination or pre-treatment steps when the material is intended for agricultural, biorefinery, or thermal conversion applications [26,28,31].

4.4. Lignocellulosic and Carbohydrate Composition

The lignocellulosic composition of *P.o.* waste reflects its structure as a marine seagrass rich in structural polysaccharides, reflecting its potential as a sustainable biomass feedstock.

Overall, the combined lignocellulosic matrix generally accounts for a significant proportion of the organic matter, often exceeding 60–80% of the dry biomass (Table 2). The biomass typically contains cellulose levels ranging from moderate to high, forming a substantial portion of its carbohydrate fraction (30–50%) and contributing to its fibrous me-

chanical properties. Hemicellulose content is also significant (12.85–21%), consisting largely of xylans and other marine-adapted polysaccharides that are more easily hydrolysable than cellulose [26,29,32,35,36].

Table 2. Lignocellulosic composition of *Posidonia oceanica* biomass reported in different studies.

Refer.	<i>P.o.</i> Source	Cellulose (%)	Hemicellulose (%)	Holocellulose (%)	Lignin (%)
[26]	Istrian Peninsula (Croatia)	40.03	18.20	-	29.13
[27]	Kefalonia (Greece)	41.1	-	60.5	28.80
[29]	Chott-Meriem (Tunisia)	38.00	21.00	-	27.00
[32]	Northern coast of Tunisia	40.00	19.00	-	30.00
[33]	Monastir (Tunisia)	40.00	-	61.8	29.80
[35]	Chat-Mariem (Tunisia)	-	18.10	-	34.20
[36]	Türkiye	41.52	12.85	-	28.57

Lignin levels tend to be lower than in terrestrial woody plants but still represent an important fraction (27–34.20%), influencing recalcitrance during biochemical conversion processes. The lignin polymer exhibits a high degree of p-hydroxy benzylation, contributing to its distinct chemical behaviour in comparison to terrestrial lignin. Collectively, these proportions define *P.o.* waste as a carbohydrate-rich, moderately lignified lignocellulosic resource [26,27,29,32,33,35,36].

In addition to structural polysaccharides, *P.o.* waste contains non-structural carbohydrates, including simple sugars or monosaccharides such as glucuronic acid and rhamnose, and other soluble compounds. However, these are typically present in lower quantities due to leaching during prolonged seawater exposure [3,35,37].

4.5. Macronutrients and Trace Elements

The macronutrient and trace element composition of *P.o.* waste reflects its dual nature as a lignocellulosic marine plant and as material exposed to seawater and sediment during senescence and beach accumulation.

Macronutrients such as nitrogen (N) and phosphorus (P) are present but generally at low to moderate levels. Nitrogen content typically ranges between 1.2 and 1.8 mg·kg^{−1}, limited due to the plant's slow growth and the leaching of soluble compounds during seawater immersion. P values range between 0.10 and 0.18 mg·kg^{−1}. Potassium (K) and sodium (Na) levels (0.8–1.5 mg·kg^{−1}), however, tend to be elevated relative to terrestrial biomass due to ionic exchange with seawater. Therefore, their concentrations decline significantly after washing or rainfall exposure. Calcium (Ca) and magnesium (Mg) constitute important inorganic components (1.0–2.0 and 0.3–0.6 mg·kg^{−1}, respectively), often associated with carbonate deposits and structural tissues, contributing to the relatively high ash fraction characteristic of beach-cast residues [3,26].

Notably, this seagrass acts as a sink for trace elements, with accumulation patterns varying significantly among organs (leaves, rhizomes, and roots) and environmental exposure, which suggests that *P.o.* detritus may contribute to trace-element cycling in marine ecosystems. Trace elements such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) are commonly detected in low concentrations, reflecting both natural uptake from the marine environment and the binding capacity of the plant's cell-wall matrix. Elements like strontium (Sr) and silicon (Si) may be comparatively enriched owing to seawater composition and sediment contact. In most cases, heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) occur at low or trace levels, though localised environmental conditions can influence their accumulation [9,28,38].

Overall, the mineral profile of *P.o.* waste is defined by moderate nutrient content, high calcium- and magnesium-based mineral fractions, and low but diverse trace element concentrations, shaped by both biological composition and environmental exposure.

4.6. Protein and Lipid Composition

The protein and lipid fractions of *P.o.* waste are relatively low compared with its dominant lignocellulosic and mineral components, reflecting the plant's structural role as a marine seagrass and the leaching effects of seawater exposure.

Protein content is typically modest, often reported in the range of 3–8% of dry mass, depending on tissue type, degree of degradation, and the extent of washing or weathering. Proteins are more concentrated in younger leaf tissues, but beach-cast residues tend to exhibit substantially reduced nitrogenous compounds after prolonged immersion periods due to microbial activity and photodegradation.

The lipid fraction is likewise low, generally occurring at 0.5–2% of dry mass. Most lipids present are structural membrane lipids rather than storage lipids, and many are subject to rapid oxidative and microbial breakdown during seawater exposure and beach deposition. Long-chain fatty acids, wax esters, and minor sterols may be present in trace amounts, but they represent only a small proportion of the total organic matter.

Overall, the low protein and lipid contents of *P.o.* waste distinguish it from nutrient-rich marine macroalgae and highlight its composition as a carbohydrate-dominated, structurally oriented biomass with minimal extractable biochemical fractions [39,40].

4.7. Other Bioactive Compounds

In addition to its dominant lignocellulosic and mineral fractions, *P.o.* waste contains a variety of bioactive secondary metabolites that reflect the species' adaptive responses to the marine environment. Among these, phenolic compounds are particularly abundant (5–25 mg GAE·g^{−1}), including phenolic acids, flavonoids, and tannin-like molecules that persist even in senescent or beach-cast material. These compounds have been found to have antioxidant, antimicrobial, and UV-protective functions in the living plant and thus partially remain in the detritus despite degradation processes. The waste also retains measurable levels of phytosterols (0.1–0.5%), most notably β -sitosterol and related sterol derivatives, which contribute to membrane stability and exhibit antioxidant potential. Minor quantities of terpenoids, fatty acid derivatives, and lipophilic pigments, such as carotenoid residues and chlorophyll-derived products, are detectable in trace to low (mg·g^{−1}) quantities, although their abundance is reduced due to photo-oxidation and leaching during seawater exposure [41–44].

Overall, the residual presence of these bioactive metabolites, particularly phenolics and sterols, suggests their potential value for extraction-based applications and bioactive polymer formulations.

5. Socioeconomic Impact of *P.o.*

Despite their ecological importance, the accumulation of banquettes in tourist areas often generates conflicts with economic activities, such as sun and beach tourism, leading local authorities to organise their periodic removal [7,11,45].

The removal of banquettes represents a considerable economic burden for coastal municipalities. Various studies report that large volumes of stranded biomass are collected each year (Figure 5), particularly in areas where meadows are in better ecological condition and waters are cleaner [41]. Each km² of *P.o.* meadow can deliver more than 125 kg of dry biomass per metre of coastline annually, forming banquettes that are estimated to cover up to 50.000 km² of Mediterranean sandy shores [3,46]. For example, in Sardinia during 2004,

approximately 106.000 m³ of banquettes were removed from 114 km of beaches in a single season, using heavy machinery and depositing the remains in landfills [14,47].

This practice not only entails high transportation and disposal costs but also results in the loss of organic matter, nutrients, and trapped sediments, which can range from 0.5 to 1725 m³ depending on the beach [48]. Furthermore, the use of heavy machinery flattens the beach profile, disrupts the natural exchange of sediments, and makes the area more vulnerable to storms and coastal erosion [45]. Paradoxically, these operations, which aim to maintain beach aesthetics, can reduce its natural resilience, generating additional coastal protection costs [49].



Figure 5. Mechanical removal of *P.o.* residues from Cala Gamba. Source: Chixoy [CC BY-SA 4.0] (Wikimedia Commons) [50].

From a social perspective, the presence of banquettes and aegagropiles is often perceived negatively by tourists, who associate them with pollution or poor water quality, when in reality they indicate a healthy marine ecosystem with clean, transparent water [26]. Their accumulation can produce unpleasant odours, mainly due to the hydrogen sulphide release, and promote insect proliferation, such as beach flies, increasing the perception of nuisance [15,26].

For this reason, local authorities face pressure from the tourism sector to remove them during the high season, even though in many areas removal is prohibited between October and March to protect coastal ecosystems [41]. This situation highlights the need for environmental education campaigns to correct misperceptions and promote the acceptance of these natural structures as part of the coastal landscape [51].

Historically, *P.o.* leaves were used for multiple purposes: as insulation material in construction, as a substitute for straw and compost in agriculture, as mattress and pillow filling, for packaging, animal feed, and even as raw material for paper production [26]. Today, however, most of this biomass is treated as municipal waste and deposited in landfills or incinerated, resulting in loss of organic matter and the emission of pollutants [38,52].

Recent strategies focus on valorising it within a circular economy framework. Options include the production of agricultural amendments, energy generation through anaerobic digestion or combustion, and the development of bio-based materials such as bioplastics, biocomposites, and bio-adsorbents for environmental remediation [3,52]. These alternatives not only reduce reliance on landfills but can also create green jobs and generate value-added products by transforming waste into a resource [7].

The management of *P.o.* waste varies considerably across the Mediterranean and is subject to regulatory frameworks that seek to balance conservation and tourism use. *P.o.* plays a fundamental role in coastal ecosystems, and its meadows have been declared a protected habitat at the European level under the Habitats Directive (92/43/CEE). This habitat type, known as “*Posidonia* grasslands” (code 1120), is considered a priority for biodiversity conservation [53,54]. This protection is reinforced through EU directives and

national laws in several countries, including Croatia, where *P.o.* is strictly protected under the Nature Protection Act and EU legislation on the conservation of habitats and wild fauna and flora [12,26]. In France, the species is strictly protected, and its removal from beaches is prohibited [54], while in Spain it falls under a special protection regime, requiring technical justification for any extraction [54].

In Italy, *P.o.* is considered a bioindicator species to assess the ecological status of marine systems under the EU Water Framework Directive (2000/60/EU) [54]. National legislation, through the “Save the Sea Law,” allows the reintroduction of naturally deposited plant biomass on beaches, promoting its recovery and reuse as a resource. Furthermore, Sicilian Regional Administration Circular No. 35792/2009 proposes management options, including the use of this biomass in landscape reconstruction, as an amendment in agriculture, or in environmental restoration works in coastal areas, according to Legislative Decree 75/2010 and Article 13 of Law No. 88 of 7 July 2009 [52]. In Greece, protection of *P.o.* is achieved indirectly through the Biodiversity Conservation Act and Natura 2000 regulations [7,54].

In this context, integrated management proposals such as the ECOLOGICAL BEACH model have been developed [51,54]. These proposals recommend maintaining banquettes in situ wherever possible and removing them only in areas of intensive tourist use. The proposals also recommend promoting banquettes as a resource, combining ecological, technical, and social perception criteria in order to minimise the negative impacts of their removal [51].

6. Valorisation Technologies for *P.o.*

6.1. Animal Feeding

Over the past decade, some studies have explored the environmental and economic advantages of reusing *P.o.* banquettes (naturally accumulated seagrass residues on Mediterranean coasts) as alternative livestock feed for small ruminants, contributing to the circular bioeconomy by converting coastal plant residues into a useful agricultural resource adapted to Mediterranean environments. The following research studies provide the most comprehensive scientific basis for this topic.

Early studies by Castillo et al. [55,56] characterised the chemical composition of the banquettes, revealing low protein (3–5%), high crude fibre (40–45%), and high ash (25–30%) contents. The biomass waste has abundant minerals, both macro (calcium, magnesium, and sodium) and trace elements (iron, zinc, and copper). These works highlighted the need for washing and drying to reduce salinity and confirmed the potential of banquettes as a local source of fibre and minerals for ruminant maintenance diets [55,56]. However, the authors cautioned that due to its low protein content and variable salt levels, *P.o.* should be used as a partial substitute, not sole forage source. Building on these findings, these authors conducted a preliminary feeding trial with dairy goats [16]. They evaluated the metabolic, nutritional, and productive effects of incorporating *P.o.* banquettes into the diets of dairy goats. The study showed that up to 450 g·day^{−1} of biomass waste can safely replace cereal straw without affecting feed intake and milk production. Moreover, the inclusion of *P.o.* into the diet improved milk quality (increased fat content) and its antioxidant capacity, supporting its use as a functional and sustainable feed ingredient. Subsequently, these authors extended their previous findings in dairy goats to another ruminant species [57]. Specifically, they evaluated the nutritional value and metabolic impact of incorporating *P.o.* banquettes into the diet of adult sheep (ewes) by replacing 15%, 30%, and 60% of the forage with this marine biomass. Results indicated that inclusion levels of up to 30% of total forage in sheep diets did not affect intake, digestibility, or metabolism. On the contrary, a reduction in performance and altered nitrogen balance were obtained at higher levels (60%). These findings defined the maximum safe inclusion level and highlighted the need

to monitor mineral intake to prevent overload. More recently, the authors summarised previous findings and discussed the role of *P.o.* as a natural forage resource for small ruminants, promoting circular bioeconomy approaches and sustainable feeding systems in Mediterranean livestock production [58].

A few complementary research studies were carried out based on previous nutritional works of Castillo and co-workers, which reinforced previous findings and extended the evaluation to dairy product quality and functional characteristics. Firstly, Van Eldik et al. [59] demonstrated that feeding goats with *P.o.* not only maintains performance but also adds functional value, improving milk fat composition, antioxidant capacity, and cheese stability, offering a sustainable strategy to enhance dairy product quality through the reuse of this marine biomass. Secondly, Hachana et al. [60] demonstrated that partial inclusion of *P.o.* residues in the diet of dairy goats maintained milk yield while increasing fat content and antioxidant capacity. This study confirmed that *P.o.* is not only a low-cost fibrous feed but also a functional ingredient capable of enhancing animal oxidative balance and product quality [60].

6.2. Bioactive Compound Extraction

As previously shown, the chemical analyses of *P.o.* (leaves, rhizomes, and detrital material) have revealed a wide array of compounds, including polysaccharides, bioactive peptides, fatty acids, phenolic acids, flavonoids, and tannins. The plant has recently emerged as a valuable natural source of bioactive compounds with potential benefits for human health. In addition, extracts from waste biomass have been demonstrated to maintain activity even post-mortem. The following studies highlight the sustainable valorisation of this marine resource for different industrial (nutraceutical, cosmetic, and pharmacological) relevance applications. Nevertheless, the translation of these findings into real-world applications still requires standardised extraction protocols, full chemical characterisation, toxicological evaluation, and in vivo validation.

6.2.1. Cellulose

Some studies demonstrated the feasibility of transforming *P.o.* residues into valuable cellulose-based materials using green chemistry and circular bioeconomy principles.

Over the past decade, research has progressively demonstrated that *P.o.* represents an abundant and renewable lignocellulosic resource suitable for sustainable material production. Early work by Khiari et al. [61] established the feasibility of valorising vegetal residues, including *P.o.*, as alternative cellulose sources. Their study optimised alkaline and bleaching treatments to isolate high-purity cellulose, providing the basis for obtaining cellulose derivatives such as cellulose acetate. Building on this foundation, Coletti et al. [62] demonstrated the conversion of *P.o.*-derived cellulose into functional polymers, successfully synthesising cellulose acetate and glycidyl methacrylate (GMA)-grafted cellulose. These materials exhibited good mechanical and optical properties, confirming that seagrass biomass could substitute terrestrial cellulose in polymer chemistry and bioplastics development [62].

Subsequent studies shifted toward nanocellulose production, with Bettaieb et al. [63] preparing cellulose nanocrystals (CNCs) from *P.o.* through controlled acid hydrolysis. The resulting CNCs displayed high crystallinity, nanoscale dimensions, and favourable thermal stability, supporting their utility in composite reinforcement. Benito-González et al. [64] further advanced CNC production by developing more sustainable extraction protocols that reduced chemical consumption while still yielding high-quality nanocrystals capable of forming strong, transparent nanocellulose films.

The resulting CNCs showed high crystallinity, nanoscale dimensions, and excellent mechanical performance when processed into transparent films with strong tensile strength and low water vapour permeability. This work demonstrated that even partially purified cellulose could yield nanocellulose films with desirable physical properties, linking *P.o.* valorisation to circular bioeconomy strategies [64]. Meanwhile, Tarchoun et al. [65] extracted microcrystalline cellulose (MCC) from the biomass, obtaining a material with good crystallinity and physicochemical properties comparable to terrestrial MCC, validating the seagrass as a viable feedstock for cellulose-based industrial applications.

Advancing toward greener processing, Camarena-Bononad et al. [4] employed subcritical water extraction (SWE) as an eco-friendly technique to recover cellulose fibres from *P.o.* residues. SWE enabled selective hydrolysis of hemicellulose and partial delignification without harsh chemicals, producing cellulose with high crystallinity, good fibre integrity, and minimal mineral contamination. These fibres were further suitable for mechanical refinement and functionalisation into biocomposites. In parallel, Mnaïki et al. [35] expanded the valorisation concept by characterising the integral composition of *P.o.* balls, or aegagropiles (the fibrous detritus formed naturally along Mediterranean shores). Their results revealed significant cellulose and lignin content, along with extractable polyphenols and minerals, positioning this by-product as a multifunctional biomass for cellulose extraction, energy recovery, and bioactive compound isolation [35].

Together, these studies portray *P.o.* as a multifunctional marine lignocellulosic resource that can be transformed into high-value cellulose, nanocellulose, and derivative materials through increasingly sustainable methods. The integration of chemical, physical, and subcritical water-based extractions highlights a clear evolution toward green, circular biorefinery models, enabling the full utilisation of this abundant marine biomass for biodegradable polymers, films, composites, and bio-based products [35,36].

6.2.2. Bioactive Peptides

P.o. has recently been identified as a source of bioactive peptides with dual antimicrobial and anticancer potential [66]. The authors isolated and characterised peptide fractions from leaf extracts that showed strong inhibitory effects against Gram-positive and Gram-negative bacteria. Some peptides likely act by disrupting microbial membranes. In human cancer cell lines, the extracts induced apoptosis through mitochondrial pathways. These findings reveal that *P.o.* produces multifunctional peptides combining antimicrobial and cytotoxic properties, supporting its value as a renewable marine source of therapeutic biomolecules [66].

6.2.3. Polyphenols

Research over recent years has established *P.o.* as a rich and renewable source of polyphenolic compounds with remarkable antioxidant and bioactive potential. Early work by Benito-González et al. [44] demonstrated that even senescent and stranded *P.o.* biomass retains a complex profile of phenolic acids and flavonoids, including chicoric, caffeic, ferulic, gallic, and p-coumaric acids, along with quercetin and myricetin derivatives. These compounds conferred strong antioxidant and antimicrobial activities, confirming that beach-cast material could serve as a sustainable raw source of natural antioxidants. Expanding on these findings, Messina et al. [67] analysed aqueous and hydroalcoholic extracts from beach-cast leaves, revealing that phenolic-rich fractions exhibited significant radical-scavenging and metal-chelating abilities. The authors reported that the antioxidant power of *P.o.* extracts paralleled their total phenolic content, suggesting that the synergistic interaction of diverse phenolic classes, rather than single compounds, drives their biological effects. Further refining this understanding, Kevrekidou et al. [68] compared

extracts from living and beach-cast leaves to evaluate their polyphenolic composition and antiproliferative activity. Using UHPLC-DAD analysis, they identified major phenolics, such as chicoric, caftaric, p-coumaric, ferulic, and trans-cinnamic acids, along with rutin and quercetin glycosides. Although living-plant extracts showed the highest antioxidant and cytotoxic activity against intestinal cancer cells (LS174), necromass extracts retained considerable bioactivity, demonstrating selective inhibition of cancer cell proliferation with minimal effects on non-tumoral cells. These results underscored the persistence of bioactive phenolics in aged biomass and their potential for therapeutic applications [68].

Adding to the chemical diversity of this seagrass, Elabbar and Alaspaly [69] reported for the first time the isolation of decyl gallate and 4-ethoxycoumarin from *P.o.* collected on the Libyan coast, expanding the known spectrum of phenolic and coumarin derivatives in this species. Along with previously identified compounds such as sinapinic, chlorogenic, and syringic acids, these newly described molecules highlight the species' capacity to produce structurally diverse secondary metabolites with potential antimicrobial and antioxidant relevance.

Collectively, these studies demonstrate that *P.o.* is not only an ecological keystone species but also a valuable marine phytochemical reservoir, especially rich in phenolic acids, flavonoids, and coumarin derivatives. Both living and stranded biomass maintain notable antioxidant, antimicrobial, and antiproliferative properties, reinforcing their potential as sustainable natural sources of polyphenols that can be used within a circular-bioeconomy framework [68,69].

6.2.4. Other Compounds and Beneficial Properties

Beyond antioxidation, Vasarri et al. [70] emphasised the anti-inflammatory potential of *P.o.* extracts, showing down-regulation of iNOS and COX-2 expression and inhibition of NF- κ B activation in stimulated immune cells. These effects translate into reduced inflammatory mediator production and protection against oxidative damage. Parallel studies by both groups also note antimicrobial activity, with inhibition of bacterial and fungal growth attributed to synergistic phenolic interactions and possible contribution from minor lipidic components.

Moreover, *P.o.* extracts exhibit anticancer and cytoprotective properties. Vasarri et al. [70] described reduced proliferation and migration of cancer cell lines (neuroblastoma, fibrosarcoma, and colon carcinoma) and suggested involvement of autophagy pathways mediated by modulation of PI3K/Akt and ERK signalling. The authors also reported antidiabetic and antiglycation effects, as extracts suppressed advanced glycation end-product (AGE) formation and improved oxidative balance in diabetic models. Benito-González et al. [44] confirmed that similar bioactivities persist in waste-derived extracts, supporting their use as a circular-bioeconomy resource.

6.3. Biochar and Activated Carbon Production

Biochar is a carbon-rich, porous material produced through the thermal decomposition of biomass under limited oxygen conditions (pyrolysis). Its structure, dominated by aromatic carbon, makes it chemically stable and resistant to degradation, allowing long-term carbon sequestration.

Several studies have demonstrated that *P.o.* biomass, once properly pre-treated, can be transformed into a sustainable material for soil improvement, carbon sequestration, water remediation, and resource recovery. The standardisation of washing, pyrolysis, and activation procedures is crucial to ensure product quality and reproducibility, while long-term field studies are needed to validate their agronomic and environmental performance [71,72].

Biochars from *P.o.* are produced under an inert gas atmosphere with a heating rate of $5\text{--}10\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$, final temperatures ranging from 300 to 600 $^{\circ}\text{C}$, and a residence time of 60 min. These conditions were selected to optimise the values of specific surface area and total pore volume [71–78], as was supported by previous studies on lignocellulose biomass pyrolysis [73]. Table S1 summarises the experimental conditions applied during the production of biochar derived from *P.o.* biomass, along with its resulting physicochemical properties.

Recent studies consistently demonstrate that *P.o.* beach waste is a viable marine feedstock for the sustainable production of biochar. Moltó et al. [71] and Ilay [72] emphasise that an essential initial step is the pre-washing of the biomass to reduce its naturally high salinity, particularly chlorides and sodium, which would otherwise hinder its agronomic use. After desalination, *P.o.* residues can be effectively pyrolysed at moderate to high temperatures (300–500 $^{\circ}\text{C}$), producing biochar with alkaline pH, increasing aromaticity and carbon stability at higher temperatures, and structural features suitable for soil amendment. Ilay [72] further shows that *P.o.* biochar has moderate nutrient content, adequate porosity, and agronomic properties comparable to or better than other low-cost marine wastes, though its ash content requires attention. Complementing these thermochemical and agronomic findings, Pizzanelli et al. [74] demonstrate that both physical and chemical activation significantly modify the structure and surface chemistry of *P.o.*-derived biochars. Although its higher mineral fraction leads to different activation responses compared with woody feedstocks, activation enhances aromatic ordering and introduces functional groups that improve the material's potential for environmental remediation. Collectively, these studies indicate that *P.o.* can be revalorised into stable and functional biochars suitable for both soil improvement and engineered carbon applications while offering an environmentally beneficial strategy for managing coastal seagrass accumulations [74].

Recent research highlights the versatility of *P.o.* residues as effective sorbent materials for water treatment. Cataldo et al. [75] demonstrated that biochars produced from low-cost biomass exhibit favourable surface chemistry for removing toxic metals, offering a sustainable alternative to conventional adsorbents. Building on this, Photiou et al. [76] showed that thermally treated *P.o.* residues efficiently remove phosphate from synthetic and real wastewater, supported by enhanced alkalinity and metal oxide content. Cataldo et al. [77] further confirmed that *P.o.*-derived biochar achieves high hydrocarbon removal from synthetic bilge water due to its porous, hydrophobic structure. Extending these applications, Muratore et al. [78] found that the same biochar effectively adsorbs rare earth elements, showing strong affinity for ions such as La^{3+} , Nd^{3+} , and Dy^{3+} .

Collectively, these studies demonstrate that *P.o.* residues (whether thermally treated or converted into biochar) represent a versatile, low-cost, and sustainable platform for removing nutrients, metals, hydrocarbons, and strategic elements from contaminated waters.

In addition, previous studies have demonstrated that biochar from *P.o.* residues can be successfully converted into activated carbons using both chemical [74,79–82] and physical activation [81,83]. In this way, activation has been shown to produce activated carbons with highly specific surface areas and increased micro-, meso-, macro-, and total porosity, depending on the activation agent and experimental conditions. Table S2 summarises the main experimental conditions used during the activation process together with key physicochemical properties of the resulting product. These *P.o.*-derived activated carbon materials have exhibited promising adsorption capacities for environmental applications to remove different pollutants such as organic dyes [80,81] and heavy metals [82,83].

6.4. Bio-Composites Production

Bio-composites derived from *P.o.* have been extensively studied over the past decade as researchers explored ways to valorise this abundant Mediterranean biomass into functional reinforcement for polymeric, thermoplastic, cementitious, and bio-based matrices. Early work by Khiari et al. [84] evaluated *P.o.* lignocellulosic particles to reinforce a commercial biodegradable thermoplastic matrix used for the production of plastic films. The results showed an increase in the thermomechanical properties of the thermoplastic matrix. Later, Puglia et al. [85] confirmed the feasibility of incorporating *P.o.* fibres into polyethylene when compatibilised with maleic anhydride, improving stiffness and interfacial adhesion while confirming the suitability of beach-cast leaves as a renewable reinforcement source. Subsequent studies expanded the scope to environmentally friendly epoxy binders, where *P.o.* residues enabled the manufacture of fibreboards with adequate mechanical integrity and dimensional stability [86]. Research on biopolymers such as PHBV and PLA showed that incorporating *P.o.* fibres generally increases modulus and reduces brittleness, although interfacial incompatibility can limit tensile strength at higher loadings [87,88]. Additional work on PMDI-bonded composite boards confirmed that leaves can be processed into lignocellulosic panels with satisfactory internal bond strength and moisture performance [6]. Valorisation of aegagropiles (the naturally formed sea balls of *P.o.*) demonstrated their effectiveness as reinforcements for protein-based matrices, enhancing stiffness and thermal stability [89].

In building materials, *P.o.* fibres improved flexural strength, toughness, and thermal insulation in gypsum composites, supporting their suitability for lightweight, low-impact construction products [90]. More recent research focused on tailored fibre preparation. Purification of *P.o.*-derived cellulose improved crystallinity, dispersion, and stiffness in PLA composites, though with reductions in toughness [91]. Similarly, compatibilisers such as maleic anhydride-grafted polymers significantly enhanced adhesion and strength in HDPE composites [92]. Chemical and physical fibre treatments (including alkaline activation, bleaching, and silanisation) further elevated mechanical and thermal performance, confirming the importance of surface engineering [36]. Thermoplastic processing studies showed that optimised fibre loading can yield viable reinforcement effects while maintaining processability [93].

Comprehensive reviews summarised these findings, emphasising consistent benefits—mechanical enhancement, reduced density, improved thermal behaviour, and potential biodegradability—while noting persistent challenges such as moisture sensitivity, natural variability, and limited compatibility in untreated systems [94,95]. Collectively, these studies position *P.o.* as a promising, regionally abundant bioresource for sustainable composite development.

6.5. Bioenergy Production

6.5.1. Biofuel Production

Overall, available evidence indicates that *P.o.* residues possess proven potential for bioethanol, bio-oil, and biodiesel production. The integration of these conversion pathways within coastal biorefineries could transform an environmental residue into a regionally valuable, sustainable energy resource.

Pilavtepe et al. [96] investigated the conversion of *P.o.* residues into bioethanol through a combination of dilute acid pre-treatment, enzymatic hydrolysis, and yeast fermentation. Using 1% H_2SO_4 at 120 °C followed by cellulase hydrolysis, the process released up to 39 g·L⁻¹ of reducing sugars. Fermentation with *Saccharomyces cerevisiae* achieved ethanol yields corresponding to 62% of the theoretical value, with a productivity of 0.76 kg·m⁻³·h⁻¹. The study demonstrated the technical feasibility of using this marine biomass as a lignocel-

lulosic feedstock. Although technically feasible, optimisation of pre-treatment to minimise inhibitors and enzyme cost reduction remains critical [96].

Recent studies have explored the thermochemical conversion of *P.o.* residues into biofuels through various pyrolytic approaches. Chiodo et al. [97] characterised the thermal decomposition of *P.o.*, reporting bio-oil yields of about 40 wt.% at 500 °C and highlighting its high oxygen and ash content as factors affecting oil stability. Zaafour et al. [32] demonstrated that co-pyrolysis with waste frying oil improved liquid yields up to 37 wt.% and increased hydrocarbon content through synergistic interactions. Fulignati et al. [98] confirmed the suitability of *P.o.* egagropiles as marine waste feedstock, achieving 45 wt.% bio-oil with a heating value near 24 MJ·kg⁻¹. More recently, Gallorini et al. [30] compared conventional and microwave-assisted pyrolysis, showing that microwave heating enhanced bio-oil yield (~50 wt.%), reduced oxygen content, and improved energy efficiency. Collectively, these studies demonstrate that *P.o.* represents a promising yet underutilised marine biomass for renewable fuel production via advanced pyrolysis technologies.

In addition, Masri et al. [99] proposed a seagrass-based biorefinery concept using *P.o.* as a nutrient source for cultivating oleaginous microorganisms capable of producing single-cell oils (SCOs). Hydrolysates derived from processed seagrass biomass were shown to support microbial growth and lipid accumulation, with certain strains reaching lipid contents comparable to conventional SCO feedstocks. The resulting oils contained fatty acid profiles suitable for biodiesel and oleochemical applications, particularly rich in C16-C18 chains [99].

6.5.2. Direct Combustion

Scientific studies on the combustion of *P.o.* have evolved from early exploratory research to comprehensive evaluations of its thermochemical behaviour and energy potential. Ntalos and Sideras [100] were among the first to investigate the reuse of *P.o.* residues as a raw material for both wood composites and thermal energy production. Their results highlighted the material's high content of salts, sand, and minerals—characteristics that significantly influence combustion efficiency and mechanical performance. They recommended pre-treatment steps, such as washing, drying, and sieving, to improve its suitability as a sustainable biomass resource. Building on this foundation, Plis et al. [101,102] carried out a detailed thermochemical characterisation using thermogravimetric analysis (TGA) coupled with mass spectrometry and FTIR. TGA of *P.o.* showed an initial mass loss of about 8–10 wt.% below 110 °C, attributed to moisture removal. The main devolatilisation stage occurred between 200 and 400 °C, accounting for approximately 45–55 wt.% mass loss due to the thermal decomposition of cellulose and hemicellulose fractions. A slower mass loss of around 10–15 wt.% was observed up to 600–700 °C, associated with lignin degradation and char oxidation. The final residue was relatively high (25–30 wt.%), reflecting the significant ash and mineral content of *P.o.*, which strongly influences its combustion behaviour [101,102]. They identified the main thermal degradation phases of *P.o.*—moisture evaporation, volatile release, and char combustion—and pointed out its moderate calorific value and high ash fraction, which may cause slagging and corrosion in combustion systems. These findings established a scientific basis for further experimental studies. Later, Jeguirim et al. [103] investigated the thermal degradation kinetics of *P.o.* under inert and oxidative atmospheres, providing valuable insight into its combustion mechanisms. Through TGA, they determined activation energies ranging from 80 to 140 kJ·mol⁻¹ and demonstrated that the mineral composition of the biomass increases ignition temperature and affects oxidation rates. The study emphasised the importance of controlling combustion conditions and applying pre-treatment to achieve more efficient energy conversion. In a subsequent study, Plis et al. [102] combined laboratory thermogravi-

metric analysis with pilot-scale combustion in a bubbling fluidised-bed reactor to assess combustion performance and gaseous emissions. The results showed that *P.o.* can burn stably after appropriate pre-treatment, producing emissions of CO₂, CO, NO_x, and SO₂ within acceptable limits. The research confirmed the technical feasibility of using this biomass for energy production while stressing the need to reduce chlorine and sulphur contents to avoid fouling and corrosion. More recently, Voca et al. [26] expanded the scope of previous work by examining the physicochemical and energetic properties of *P.o.* waste collected from Mediterranean beaches. They reported a lower heating value (14–15 MJ·kg^{−1}) and an ash content of more than 20%, indicating moderate energy potential but challenges for direct combustion in conventional boilers. The authors suggested co-combustion with woody biomass and washing treatments to improve combustion stability and energy yield.

Taken together, these studies reveal that *P.o.* possesses measurable energy potential as a renewable source, though its high mineral and salt content poses significant technical limitations. Due to its marine origin, *P.o.* contains significant amounts of chlorine, sulphur, and various trace metals, which can lead to the formation of toxic air pollutants such as dioxins and furans during the direct combustion process. While specific quantitative emissions for *P.o.* combustion are still limited in the literature, it is well established that the presence of chlorine in marine biomass promotes the formation of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) under typical combustion conditions [104]. Moreover, high ash content and the presence of alkali and alkaline-earth metals can affect slagging, fouling, and the emissions of inorganic pollutants. Pre-treatment methods and co-firing strategies are therefore essential to enhance combustion efficiency, minimise ash-related problems, and enable sustainable valorisation of this abundant Mediterranean biomass.

6.5.3. Anaerobic Digestion

Several studies have examined the potential of *P.o.* residues as feedstock for anaerobic digestion (AD), highlighting both the opportunities and the limitations of this lignocellulosic marine biomass. AD research of *P.o.* has progressively evolved from a conceptual assessment of its energy potential. In this sense, Balata and Tola [105] approached the topic from a cost-opportunity perspective, identifying AD as a potential valorisation route for beach-collected *P.o.* in tourism-oriented coastal areas. They emphasised that while AD could reduce the costs associated with waste management and generate renewable energy, the available data on methane yields and process efficiency are scarce, and the high mineral and inert content of beach wrack introduces uncertainty into feasibility assessments. Responding to this knowledge gap, De Sanctis and Di Iaconi [106] evaluated *P.o.* residues in laboratory-scale biochemical methane potential (BMP) tests, confirming that untreated biomass exhibits low methane yields due to its high lignocellulosic content and low nitrogen concentration, which limit microbial degradation. They observed that washing the biomass to reduce salt content had minimal impact on methane production, whereas thermal pre-treatment at 132 °C provided a moderate improvement (10–20% increase), indicating that partial breakdown of lignocellulosic fibres can enhance digestibility. Expanding on this approach, De Sanctis et al. [46] specifically investigated the integration of thermal and acid-thermal hydrolysis with AD to improve energy efficiency. Their results demonstrated that hydrolysis pre-treatment significantly increased the solubilisation of organic matter and methane yield, achieving approximately $0.241 \pm 0.065 \text{ Nm}^3 \text{ biogas} \cdot \text{kg}^{-1} \text{ VS}$, with a methane fraction of about 57%. An energy balance analysis indicated that, under optimised conditions, the energy gained from enhanced biogas production can compensate for the energy required for pre-treatment, making the process energetically favourable. More recently, De la Lama-Calvente et al. [34] addressed another key limitation of *P.o.* as a suitable AD substrate, namely its low nitrogen content. By co-digesting the seagrass

aegagropiles with nitrogen-rich substrates, such as peptone, casein, urea, or microalgal biomass, they demonstrated a dramatic increase in methane yields, from around 79 NL $\text{CH}_4 \cdot \text{kg}^{-1}$ VS for mono-digestion to 380–420 NL $\text{CH}_4 \cdot \text{kg}^{-1}$ VS for co-digestion, depending on the nitrogen source. Kinetic analysis revealed that nitrogen supplementation not only increased ultimate methane production but also accelerated the digestion process, reducing lag phases and improving microbial activity.

Collectively, these studies reveal that *P.o.* residues possess considerable potential as a renewable energy source, but their effective digestion requires process optimisation. The biomass's structural rigidity, low nitrogen content, and high mineral fraction limit its direct anaerobic biodegradability, resulting in poor methane yields under standard conditions. Nevertheless, pre-treatment methods (particularly thermal and acid-thermal hydrolysis) and co-digestion with nitrogen-rich substrates have proven capable of significantly improving methane production and digestion kinetics [105,106].

Overall, the literature suggests that AD of *P.o.* is technically feasible and environmentally attractive, but successful implementation requires careful consideration of substrate composition, pre-treatment, and nutrient balance to achieve both energy recovery and economic viability in coastal areas.

6.6. Agricultural and Horticultural Valorisation

6.6.1. Biofertiliser Production

The progressive valorisation of *P.o.* residues has followed a clear chronological trajectory, beginning with early investigations into their direct agronomic use and later expanding toward bio-stimulant, nutritional, protective, and circular-economy applications.

Serio et al. [107] provided one of the first agronomic assessments by cultivating cherry tomatoes directly in *P.o.*-based substrates. They showed that increasing NaCl concentrations influenced both yield and fruit quality, demonstrating the material's sensitivity to salinity but also its potential as a substrate when properly managed. Advancing on this line of inquiry, Gizas et al. [1] examined the hydraulic behaviour of raw and composted residues. Their results showed that uncomposted *P.o.*, particularly when combined with pumice, offered high aeration and acceptable water retention for lettuce cultivation. Despite the material's initially limited water retention, its structural porosity promoted healthy root development and showed that untreated residues could perform comparably to conventional organic substrates when physically balanced with mineral aggregates, confirming its viability as a direct substrate component [1].

A broader ecological perspective was introduced by Vecchio et al. [108], who demonstrated that beach-cast *P.o.* positively affected the germination, nutrient uptake, and growth of coastal dune species, highlighting its value as a natural amendment in restoration contexts. Later, the scope of research widened toward exploiting the bioactive properties of *P.o.* biomass. Interest in germination-focused applications grew with Marilés et al. [109], who demonstrated that *P.o.* fibres provided a suitable environment for lentil seed germination, confirming their utility as a biodegradable support material. Nearly in parallel, D'Imperio et al. [110] tested washed, shredded residues as an additive in peat-based mixes for growing *Brassica* microgreens. While the biomass yield remained similar to the control, the microgreens produced on *P.o.*-amended substrates exhibited enhanced mineral profiles, particularly in calcium, magnesium, and micronutrients. This demonstrated that the raw residue could contribute nutritional value while offering a sustainable alternative to traditional substrate components. Building on these findings, Ferrández-Gómez et al. [41] focused specifically on the bio-stimulant potential of *P.o.* extracts. Their assays with cucumber and tomato seeds revealed that low-concentration aqueous and solvent extracts significantly promoted germination and early radicle elongation. These effects indicated

the presence of growth-promoting compounds (phenolics, minerals, and polysaccharides) that could be mobilised with minimal processing. The study helped shift the perception of *P.o.* from a structural amendment toward a biologically active input. This bio-stimulant perspective was further strengthened by Ferrández-Gómez et al. [111], who explored the use of *P.o.* extract as an elicitor to mitigate aphid-induced stress in sweet pepper plants. Treated plants exhibited reduced pest pressure, increased antioxidant enzyme activities, and improved photosynthetic efficiency. These responses reflected the extract's capacity to activate plant defence pathways and reduce oxidative damage, confirming the potential of *P.o.* as a natural elicitor for sustainable crop protection [111].

Finally, the circularity of this biomass was highlighted by Ramos-Esplá et al. [112], who assessed the washing of *P.o.* residues with treated urban wastewater. This process effectively removed soluble salts and enriched the fibres with nutrients, enabling their safe reuse as biofilters or soil amendments. The work demonstrated an integrated approach that links coastal biomass management with wastewater reuse, reinforcing the environmental relevance of *P.o.* valorisation.

Altogether, these studies outline a coherent development path: from early tests proving the agronomic feasibility of raw residues, through demonstrations of their nutritional and bio-stimulant potential, to recent innovations that position *P.o.* as a multifunctional input within sustainable and circular agricultural systems.

6.6.2. Composting Material Production

Research on the composting and agricultural reuse of *P.o.* residues over the past two decades demonstrates the growing interest in transforming this abundant coastal biomass into a valuable organic resource. Table S3 presents the experimental conditions applied during the composting of *P.o.* biomass and the main physicochemical properties of the resulting compost.

Early work by Orquín et al. [113] and Castaldi and Melis [114] established that composting *P.o.* with yard or organic waste can produce stable, humified material suitable for agricultural use, provided that mixtures are balanced to improve the C/N ratio. Later, Coccozza et al. [31] demonstrated that when *P.o.* debris is mixed with residues of olive pruning and green wastes, the biomass decomposes effectively and produces a high-quality compost, non-phytotoxic and with a low heavy metal content, and is therefore a suitable product for safe utilisation as an amendment in agriculture. Subsequent studies expanded this approach to horticultural applications. Mininni et al. [115–117] showed that *P.o.*-based compost can successfully replace peat up to 30% in substrates for lettuce, melon, tomato, and basil, maintaining satisfactory germination, biomass, and nutrient uptake, while improving substrate aeration and water retention. Grassi et al. [28] confirmed its effectiveness as a soil amendment and organic mulch, enhancing soil moisture and reducing weed growth without phytotoxic effects.

Further reviews by Parente et al. [118] highlighted the potential of *P.o.* compost as a sustainable component for soilless cultivation systems, stressing its favourable structural and nutrient characteristics when desalinated and matured. Provenzano et al. [119] deepened understanding of composting mechanisms through chemical and spectroscopic analyses, confirming progressive lignocellulosic degradation, humification, and the achievement of a stable, safe product. More recent works by Peruzzi et al. [120,121] explored co-composting *P.o.* with dredged sediments, demonstrating effective stabilisation, reduced salinity, and suitability of the resulting compost as a substrate for ornamental plants. Van-nucchi et al. [122] further showed that combining *P.o.* compost with sediments in growing media improves plant tolerance, nutrient uptake, and resilience to stress, reinforcing its value as a sustainable alternative to peat.

Collectively, these studies indicate that compost derived from *P.o.* can be effectively integrated into horticultural and agricultural production when properly processed and mixed with other organic materials. Common findings include improved substrate structure, increased water-holding capacity, low pathogen levels, and reduced heavy metal content. However, the high salinity of untreated material remains a critical limitation, requiring washing, leaching, or controlled co-composting strategies. Most authors recommend limiting *P.o.* compost to 20–30% of substrate mixtures to prevent growth inhibition in sensitive crops. Overall, research supports the inclusion of *P.o.*-based compost as a renewable, eco-friendly alternative to peat, contributing to coastal waste valorisation and sustainable circular agriculture in Mediterranean environments.

6.7. Biosorbent Material

P.o. biomass has attracted growing scientific interest as a sustainable and low-cost bio-adsorbent for water treatment. Its lignocellulosic structure, porosity, and abundance of functional groups—such as hydroxyl, carboxyl, and phenolic moieties—enable interactions with a wide range of contaminants without the need to convert the material into activated carbon or biochar. Research over the last two decades has demonstrated the capacity of raw or mildly treated *P.o.* waste to adsorb diverse pollutant classes [123–144]. These include inorganic nutrients (ammonium and phosphate), heavy metals, and organic contaminants spanning dyes, antibiotics, and other pollutants. The material has also shown strong affinity for hydrophobic substances, including crude oil and petroleum derivatives, and can reduce levels of surfactants commonly found in detergents and industrial effluents. Table S4 summarises adsorption studies reported in the literature using *P.o.* as biosorbent material for the removal of different contaminants from aqueous media according to the specific pollutant nature and the relevant experimental conditions.

P.o. beach wrack has been studied as a low-cost bio-adsorbent for removing inorganic nutrients, particularly ammonium (NH_4^+) and phosphate (PO_4^{3-}), which are key contributors to eutrophication. Wahab et al. [123–125] demonstrated that raw *P.o.* fibres possess functional groups capable of binding these ions through ion exchange and surface complexation. For ammonium, adsorption efficiency increases with temperature and depends strongly on pH, favouring conditions where NH_4^+ is the dominant species. Phosphate removal also varies with pH, with higher uptake in acidic to near-neutral conditions where phosphate species interact more effectively with available adsorption sites. The authors noted the influence of competing anions and ionic strength on performance.

P.o. beach wrack has been widely investigated as a bio-adsorbent for heavy-metal removal. Allouche et al. [126] and Aydin et al. [127] confirmed that removal efficiency depends strongly on pH, metal concentration, and competing ions. More advanced studies explored modifications to enhance uptake. Pennesi et al. [128] and Kaouah et al. [129] showed that mild chemical treatments increase surface reactivity and porosity, improving metal-binding capacity. Boubakri et al. [130] demonstrated that incorporating iron-based nanoparticles (e.g., nZVI) markedly enhances removal through combined adsorption and reduction mechanisms. Recent work by Boulaiche et al. [131] further emphasised the role of surface functionalisation in optimising selectivity and kinetics.

Early work by Ncibi et al. [132] highlighted the effectiveness of raw fibres in binding metal cation dyes through ion exchange and complexation with naturally functioning groups. Subsequent studies over the past twenty years consistently demonstrate that *P.o.* waste is an effective, low-cost bio-adsorbent for removing dyes from water. Early works by Ncibi et al. [133] and Guezguez et al. [134] established the strong affinity of raw *P.o.* fibres for cationic dyes such as methylene blue and yellow 59, respectively. Subsequent studies by Cengiz & Cavas [135] and Cengiz et al. [136] confirmed high dye uptake capacities

and showed that pH, contact time, and ionic strength substantially influence removal efficiencies. Advances in material modification, such as magnetic functionalisation [137] and acid or alkaline treatments [138,139], have further improved adsorption capacities by increasing surface area, porosity, and accessible active sites. Recent contributions, including Masmoudi & Dhaouadi [81] and Vagi et al. [140], highlight enhanced performance toward both cationic and anionic dyes and emphasise improved kinetic behaviour.

In addition, some studies have been carried out on removing antibiotics from aqueous solutions. Biosorption studies were carried out in a batch system, and the effects of solution pH, biosorbent dose, antibiotic initial concentration, and contact time were studied in detail. Firstly, Krika et al. [141] evaluated both *P.o.*, unmodified versus basic-modified forms, for their possible utilisation as a cheap biosorbent for the retention of amoxicillin. The sorption equilibrium was reached after 30 min of contact time, increasing the adsorption capacity at acidic pH and using the chemically modified adsorbent. On the other hand, Ferchichi et al. [142] investigated *P.o.* as a biosorbent for tetracycline-type compounds. Antibiotic uptake was also strongly influenced by solution pH, reflecting changes in both biomass surface charge and antibiotic speciation. In fact, the optimal removal occurred under conditions that favoured the zwitterionic or cationic forms of tetracyclines, which enhanced their affinity for the *P.o.* biomass.

Finally, *P.o.* beach wrack has been evaluated as a biosorbent for hydrophobic pollutants and surface-active compounds. Ncibi et al. [143] demonstrated that raw *P.o.* fibres can remove both anionic and non-ionic surfactants through a combination of hydrophobic interactions, electrostatic forces, and the abundant lignocellulosic functional groups present on the biomass surface. Adsorption efficiencies were influenced by surfactant type, concentration, and solution pH. Complementing these findings, Ben Jmaa & Kallel [144] evaluated *P.o.* residues as a natural oil sorbent and reported high oil retention capacities relative to other plant-based materials. The fibrous structure, natural porosity, and waxy surface components contribute to a strong affinity for crude oil and petroleum derivatives. The material also demonstrated good reusability, with oil recoverable by simple mechanical squeezing.

6.8. Building Materials Production

P.o. residues can be effectively transformed into eco-friendly construction materials that combine low thermal conductivity, reduced weight, and acceptable mechanical strength. When properly cleaned and chemically treated, the fibres exhibit strong interfacial bonding with cement, polymer, or clay matrices. However, researchers also emphasise ongoing challenges, including variability of natural feedstock, sensitivity to moisture, and the need for standardisation, durability testing, and scalable industrial processes.

Research on *P.o.* as a sustainable material for construction has expanded significantly over the past decade, evolving from early experiments with cement and particleboards to a wide range of applications in insulation, composites, earthen materials, and plaster-based systems [145,146].

The pioneering work of Saval et al. [145] demonstrated the potential of seagrass residues as fillers in cement-bonded particleboards, achieving reduced density, acceptable mechanical strength, and enhanced fire resistance due to the mineral content of the fibres. Building on this, Allègue et al. [146] reinforced cement composites with *P.o.* fibres, reporting moderate improvements in tensile and flexural strength, though challenges persisted with water absorption and decreased workability caused by the fibres' hydrophilic nature. To improve fibre performance, Zannen et al. [147] investigated combined alkali and silane treatments, showing that such surface modifications increased tensile strength, reduced hygroscopicity, and enhanced fibre–matrix adhesion—critical advances for incorporating marine biomass into composite materials. Carmona et al. [148] then applied *P.o.* to thermal

insulation in flat roof systems, establishing the minimum bulk density needed to ensure mechanical stability and optimal thermal performance, confirming its viability as a natural insulating material for Mediterranean climates. At the same time, García-García et al. [86] fabricated environmentally friendly composite fibreboards using *P.o.* waste and epoxy resin, achieving improved rigidity and reduced water absorption. In parallel, Hamdaoui et al. [149] characterised the thermophysical properties of seagrass fibres, reporting low thermal conductivity and excellent hygrothermal regulation, reinforcing their suitability for insulation applications. Kuqo et al. [6] further developed polymeric methylene diphenyl diisocyanate (PMDI) composite boards using seagrass leaves, demonstrating enhanced mechanical strength and reduced density, highlighting the potential of these fibres for lightweight, high-performance biocomposites [6].

Subsequent research extended the valorisation of *P.o.* residues to new materials and contexts. Jedidi and Abroug [150] transformed seagrass balls into insulation panels, showing low thermal conductivity, good porosity, and adequate strength, while Olacia et al. [151] incorporated the fibres into adobe bricks, achieving greater crack resistance, reduced density, and improved thermal insulation. Later, Jedidi [152] applied seagrass fibres to plaster formulations, demonstrating notable improvements in both thermal and acoustic insulation properties without compromising mechanical strength. Studies on cementitious matrices continued, as Hamdaoui et al. [153] showed that seagrass fibre reinforcement improved the mechanical and thermal performance of hardened cement pastes, and Benjedou et al. [154] confirmed enhanced thermal and acoustic insulation in cement composites with *P.o.* fibres, attributed to their porous morphology and effective fibre–matrix bonding. Mayer et al. [155] compared seagrass- and wood-based cement boards, finding similar strength but superior thermal insulation and environmental benefits for the seagrass-based materials.

In the field of insulation, Mehrez et al. [156] produced panels from *P.o.* leaves that combined low thermal conductivity, lightweight properties, and moisture resistance, while Ben Hadj Tahar et al. [157] developed and evaluated seagrass-based insulation materials for Algeria, confirming their energy efficiency and durability as a locally sourced bio-insulator. Finally, Braiek et al. [158] advanced the application of seagrass fibres in clay-based composites, demonstrating that fibre incorporation reduced density and thermal conductivity while maintaining structural integrity for non-load-bearing elements.

7. Conclusions

The review demonstrates that *Posidonia oceanica* (*P.o.*), despite being traditionally managed as a problematic coastal waste, actually constitutes a marine biomass of high ecological, economic, and industrial value. Its presence on beaches—in the form of banquettes and aegagropiles—is an indicator of good environmental quality and plays an essential role in coastal protection, sediment stabilisation, and the maintenance of healthy coastal ecosystems.

However, tourist pressure has led to its systematic removal, generating high economic costs and causing the loss of ecosystem services, in addition to increasing erosion and reducing the natural resilience of beaches.

From a compositional point of view, *P.o.* comprises a lignocellulosic biomass rich in cellulose, hemicellulose, and lignin, with similar values in different regions of the Mediterranean. This opens the door to multiple routes for industrial valorisation, especially in bioprocesses and advanced materials.

The current applications of *P.o.* biomass are closely related to its chemical composition. Its high content of cellulose and hemicellulose provides a fibrous structure that supports applications such as thermal insulation materials, packing materials, and lignocellulosic

feedstock for thermochemical conversion. Its thermochemical characteristics are suitable and comparable to those of other Mediterranean biomasses (e.g., olive pomace and vineyard prunings), although its high ash content requires process optimisation. The presence of lignin contributes to structural rigidity and thermal stability, favouring its use in biochar and activated carbon production. In addition, abundant oxygen-containing functional groups (e.g., hydroxyl and carboxyl groups) on the raw biomass surface enable the direct use of *P.o.* as a natural biosorbent for the removal of dyes and heavy metals from aqueous solutions. Finally, the relatively high ash and mineral content (Ca, K, Mg, and Na) supports applications in soil amendment, composting, and construction materials, where mineral constituents are beneficial.

Therefore, the evidence gathered confirms that *P.o.* should not be considered waste but rather a strategic resource within the Mediterranean circular economy. Its valorisation contributes to reducing pressure on landfills, decreasing municipal management costs, increasing coastal resilience, promoting industrial and biotechnological innovation, and generating green jobs and new value chains.

Furthermore, the legal protection of the species and the growing scientific attention support the need for sustainable management systems that integrate conservation, environmental education, and efficient use of biomass.

Overall, this work demonstrates that *P.o.* possesses an underutilised potential, and its intelligent use can transform an environmental challenge into an ecological and economic opportunity for Mediterranean regions.

8. Future Research Directions

Despite significant progress in the characterisation and valorisation of *P.o.* residues, several knowledge gaps and technical challenges remain. Addressing these issues will require multidisciplinary approaches aimed at enhancing sustainability, scalability, and functional performance.

Future studies should focus on developing uniform, eco-friendly protocols for isolating bioactive compounds [159] such as phenolics (e.g., Deep Eutectic Solvents (DESs), Supercritical Fluid Extraction (SFE)), peptides (e.g., Enzyme-Assisted Extraction (EAE), Pulsed Electric Fields (PEFs)), and cellulose (e.g., Microwave-Assisted Extraction (MAR)). These protocols must include comprehensive chemical characterisation, toxicological assessment, and in vivo validation to ensure safety and efficacy for nutraceutical, cosmetic, and pharmaceutical applications.

Scaling up the production of nanocellulose and biocomposites with tailored mechanical and thermal properties remains a priority. Research should also address durability, moisture sensitivity, and performance under real-world conditions to enable their use in construction, packaging, and insulation.

Further research is needed to exploit *P.o.* extracts as bio-stimulants for crop protection and stress mitigation. Long-term trials should examine their effects on soil health, microbial communities, and crop productivity under diverse agronomic conditions.

Advancing pyrolysis technologies—including microwave-assisted processes—could improve bio-oil yield and quality. Similarly, co-digestion strategies with nitrogen-rich substrates should be investigated to maximise methane production and enhance anaerobic digestion efficiency.

The potential of *P.o.* residues as a bio-adsorbent for emerging pollutants, such as antibiotics, microplastics, and rare earth elements, remains underexplored. Future work should focus on functionalising biomass to improve selectivity, adsorption capacity, and regeneration performance.

Finally, the integration of multiple valorisation pathways—bioactive extraction, biochar production, biocomposites, and biofuels—within circular biorefinery frameworks represents a promising avenue. Future work should assess the techno-economic feasibility and environmental performance of such systems in Mediterranean coastal contexts.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/cleantechnol8020056/s1>. Table S1: Experimental conditions and physicochemical characteristics of biochar produced from *Posidonia oceanica*; Table S2: Experimental conditions and physicochemical characteristics for the production of activated carbon from biochar of *Posidonia oceanica* reported in the literature; Table S3: Experimental conditions and physicochemical characteristics of compost produced from *Posidonia oceanica*; and Table S4: Comparative study of adsorption experiments using *Posidonia oceanica* as biosorbent.

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