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# A comprehensive Review of Posidonia oceanica Biomass in the Mediterranean Sea: Morphological Adaptations, Phytochemical Profiles, and Agronomic Applications (2015-2025)

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**Abstract**

Posidonia oceanica (L.) Delile is a key endemic species among marine angiosperms, which are responsible for the maintenance of the ecosystem balance of the Mediterranean region. The review includes a thorough analysis of the peer-reviewed literature from 2015 to 2025 regarding the evolution, physiology, and necromass characteristics of P. oceanica including the description of the geographical location of the species in the southern Mediterranean coast. The chemical analysis shows an exclusive lignocellulosic composition with high content of macro- and microelements, as well as bioactive compounds. The phenolic profile has been proven as being highly effective in vitro antioxidants, antibacterial, and antifungal activities. Therefore, P. oceanica biomass can be considered as a source of natural biopesticides and plant biostimulants. Additionally, this paper assesses the agricultural potential of the species residues such as banquettes and Neptune balls as the sustainable component of the substrate that can partially replace peat that is not renewable. However,

some technical limitations like high tissue saltiness, heavy metals accumulation, high C:N ratio, and heterogeneity should be addressed through optimization of water treatment. Finally, the knowledge gaps that have been identified in the literature and the need for multi-site field tests and green extraction workflow are discussed.

**Keywords:** P. oceanica; seagrass biomass; chemical composition; phenolic compounds; antimicrobial activity; organic amendments; growing media; Mediterranean agriculture.

## 1. Introduction

P. oceanica is a marine Angiosperm, within the clade of Monocotyledonous, belonging to the order of Alismatales, family of Posidoniaceae. This plant is the most important endemic species of the Mediterranean Sea, protected by European legislation through the Habitat Directive 92/43/UE and classified as Priority Habitat within the Red List of the International Union for Conservation of Nature (IUCN) (Pergent et al.,2010). is the most important species of seagrass for the Mediterranean Sea's ecological coastal balance slow growing, organized in roots, rhizomes, leaves, flowers and fruits (Gobert et al., 2006 Vacchi et al., 2016). P. oceanica colonizes vast underwater areas, forming extensive meadows from the surface to 40 m depth and grows within a temperature range of 10◦C to about 30◦C. Temperature is therefore considered the central parameter controlling the geographical distribution of this species. P. oceanica beds cover between 25,000 and 50,000 km2 of the coastal areas of the Mediterranean, covering about 1.5% of the total Mediterranean Sea surface (Boudouresque et al.,2012; Bonhomme et al.,2015). This review critically synthesizes peer reviewed literature from 2015 to 2025 on P. oceanica biomass, highlighting points of consensus and controversy in mechanistic pathways, agroecosystem applications and remaining research challenges, with the aim of guiding future innovations.

This review is based on a qualitative synthesis of peer reviewed studies on P.

oceanica biomass published between 2015 and 2025. Relevant articles were identified through structured searches in major scientific databases using combinations of terms related to P. oceanica chemistry, antimicrobial activity, composting and growing media, and were selected for their focus on living tissues, beach cast residues and agricultural applications; summary values reported in the original papers were compiled and plotted as descriptive bar charts, and no new experiments or inferential statistical analyses were performed in this work.

## 2. Evolution and Biogeography

### 2.1 Evolutionary Origins

The genus Posidonia diverged from terrestrial angiosperms roughly 100 million years ago, with fossil evidence tracing its lineage to the ancient Tethys Sea. Plate tectonics led to the separation and diversification of Posidonia species, with P. oceanica becoming the only Mediterranean representative, while its closest relatives remain isolated in southern Australia (Aires et al., 2011; Celdran et al.,2015; Cantasano et al., 2022; Cantasano et al., 2023).

### 2.2 Mediterranean Endemism

P. oceanica meadows are endemic to the Mediterranean Basin, found from the Alboran Sea in the west to the shores of Egypt and Turkey in the east, and as far north as Catalonia and the Gulf of Trieste. These meadows cover an estimated 19,500 – 37,500 km², spanning a broad depth gradient down to 45 meters (Telesca et al., 2015;

Holzknecht et al., 2022; Burgués Palau, L., 2022), including documented stands along the Libyan coast near Misrata (Figure 1). Taken together, these distributional estimates highlight the exceptional spatial dominance of P. oceanica within the Mediterranean coastal zone, while also revealing pronounced regional variability in meadow extent and depth limits. Such variability likely reflects differences in hydrodynamic exposure, water clarity, and local anthropogenic pressures, which in turn shape the species' biogeographical resilience and the priorities for conservation along southern versus northern shores.

**Figure 1. P. oceanica stand along the Misrata coast (Libya), showing the local occurrence of the species in the southern Mediterranean (N32° 21,30 E15° 12,21).**

Figure 2 presents the conceptual framework used in this review. The review is conducted based on the physicochemical properties of P. oceanica biomass, its bioactive compounds, agricultural uses, current challenges, and future possibilities with respect to the circular bioeconomy. This allows the reviewer to critically assess the current literature and to pinpoint key issues that require future research attention. The framework clearly demonstrates the shift from characterizing the material to its application, which reflects the increasing need to integrate marine biomass in agriculture (Yildirim et al., 2025; Flores-Félix, 2025).

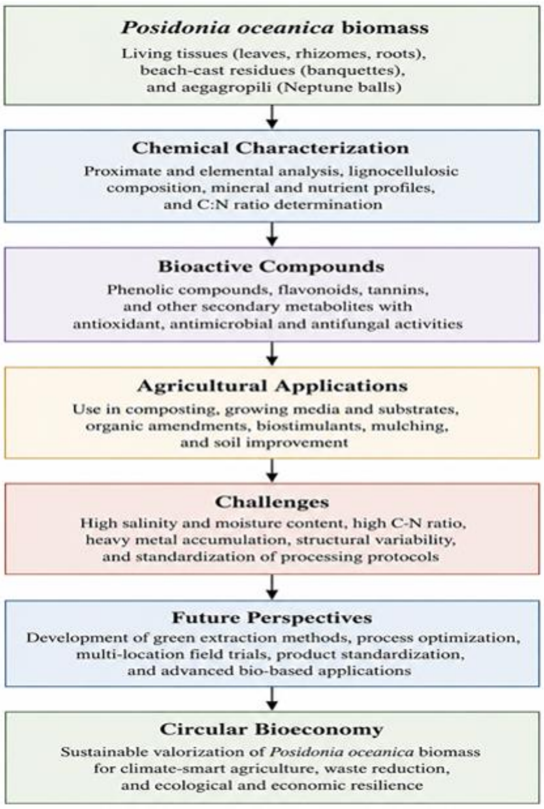


**Figure 2. Integrated framework of P. oceanica biomass characterization, utilization, challenges, and future research directions.**

## 3. Review Methodology

This study has been done through a qualitative synthesis of peer-reviewed literature on biomass of P. oceanica from the year 2015 till 2025. Articles pertaining to the topic have been identified by means of systematic search using scientific databases like Scopus, Web of Science, PubMed, and Google Scholar. Keyword combination used to retrieve articles was "Posidonia oceanica chemistry", "seagrass biomass", "antimicrobial activity", "composting", and "growing media". Selection was made on the basis of relevance to living tissue, beach-cast material, and agricultural application of P. oceanica biomass. Inclusion criteria gave more importance to research articles, review papers, and meta-analyses which contained quantitative data regarding chemical composition, profiles of bioactive compounds, and agronomical properties. Descriptive bar charts have been created using summary values obtained from articles and no new experiments nor any new inferential statistics have been conducted. This type of approach is quite common in narrative reviews for marine bioresources (Flores-Félix, 2025; Jaroslava et al., 2026).

## 4. Morphological and Physiological Adaptations

### 4.1 Plant Architecture

**Rhizomes**: Both plagiotropic (horizontal) and orthotropic (vertical) rhizomes facilitate expansion and environmental adaptation.

**Strap shaped leaves**: Leaves often exceed 1 meter, maximizing underwater light capture through a broad, photosynthetic blade and basal sheath.

**Roots**: The roots can penetrate up to 70cm into sediment, anchoring the plant and aiding nutrient uptake, while participating in the formation of a matte structure important for carbon storage and sediment stabilization. (Scanu, M. 2017; Rencoret et al.,2020; Lefebvre et al., 2023).

**Fruits**: P. oceanica produces ovoid fruits (about 2.5cm long and 1.6cm wide) with a spongy, membranous pericarp that allows buoyancy for seed dispersal. (Guerrero-Meseguer et al.,2018).

**Seeds**: Seeds are large (5 - 10mm), nondormant, and contain high nutrient reserves. Their surface has adhesive microscopic hairs to anchor to sediment. Seed reserves are used quickly during early development (Balestri et al., 2009; Guerrero-Meseguer et al.,2018) (Figuer 3).

**Figure 3. P. oceanica specimen collected from the Misrata coast (Libya), showing strap shaped leaves, rhizomes, and roots forming part of the matte structure.**

## 4.2 Physiological Innovations

**High chloroplast density**: Especially in the leaf epidermis for efficient underwater photosynthesis.

**Absence of stomata**: Gas exchange occurs across a specialized porous cuticle.

**Absence/reduction of cuticula**: Leaf blades show minimal or reduced cuticle, facilitating effective gas and nutrient exchange underwater.

**Aerenchyma tissue**: Air filled spaces in tissues allow gas transport in submerged conditions.

**Mechanical tissue**: Thick walled, lignified support cells confer resistance to physical disturbances.

**Osmotic leaf adaptations**: Leave blades have specific mechanisms to regulate osmotic pressure, supporting cell function in saline environments. (Papenbrock, J. 2012; García-Márquez et al.,2022).

**Root Modifications**: Scientific analyses of Posidonia's root systems show morphological changes such as extensive branching and greater penetration ability, which supports anchorage and effective resource uptake in soft, sandy, or muddy substrate (Celdran et al.,2015; Balestri et al.,2017; García-Márquez et al.,2022 Cantasano, N. 2023).

**P. oceanica seeds**: exhibit photosynthetic activity from the onset of germination, continuing throughout early seedling growth (Celdrán et al., 2015).

Collectively, these architectural and physiological traits explain why P. oceanica forms extremely stable, long-lived meadows compared with many faster growing seagrass species. Deep, extensively branched roots and lignified mechanical tissues anchor the matte and resist storm energy, while high chloroplast density and specialized gas exchange mechanisms sustain photosynthesis under variable light and salinity regimes, thereby underpinning both its keystone ecological role and its slow recovery dynamics after disturbance.

## 5. P. oceanica biomass

P. oceanica leaves consist of blades that are shed annually, whereas the sheaths generally remain attached to the rhizomes. The annual loss of blades generates leaf debris that accumulates along the shoreline as coastal banquettes, which play a prominent role in protecting beaches from erosion and contributing to dune construction. Eventually, much of this material is returned to the sea, where it constitutes a major source of organic matter and nutrients for surrounding coastal ecosystems and artisanal fisheries (Boudouresque et al., 2012).

In contrast, rhizome fragments together with roots and sheaths can become entangled by wave action and form ball-like structures known as egagropili. These egagropili are mainly composed of fibrous materials such as cellulose, hemicellulose, and lignin, along with significant proportions of ash and phenolic compounds (Souii et al., 2023). Their distinctive physical characteristics include a rough, felt-like texture, oval to spherical shapes, diameters ranging from a few millimetres up to about 20 cm, and low density, which allows them to float freely in seawater (Mirpoor et al., 2020; Lefebvre et al., 2021; Kumar et al., 2022).

Once shed, P. oceanica leaves have a lifespan of roughly 4–13 months and contribute to litter within the meadow alongside rhizomes and roots detached by water movement, storms, or human activities such as anchoring and trawling (Personnic et al., 2014). This necromass, equivalent to about 10–55% of meadow primary production, is largely exported from the meadow to adjacent environments (Pergent et al., 1994; Boudouresque et al., 2006, 2012, 2016; Vacchi et al., 2017).

Taken together, these studies show that P. oceanica produces substantial and structurally diverse necromass that functions both as a coastal defence mechanism and as a key vector of carbon and nutrient transfer between seagrass meadows and neighbouring marine and terrestrial habitat.

## 6. Reproduction and Dispersal

Sexual reproduction in P. oceanica occurs through hydrophilous pollination, whereby pollen is transported in the water column, a typical adaptation of marine angiosperms. Clonal propagation is equally important, as meadows expand primarily via rhizome elongation, which enhances long-term stability and population persistence. Seed formation and dispersal in P. oceanica involve several specialised adaptations that promote successful recruitment and establishment: during development, seeds accumulate substantial starch reserves, possess a mature plumule, and contain well-formed root initials, collectively facilitating rapid anchoring and growth once suitable substrates are reached. Notably, P. oceanica seeds exhibit photosynthetic activity from the onset of germination and throughout early seedling growth, increasing biomass accumulation in both developing leaves and roots. Furthermore, fruit and seed structures are adapted for long-distance transport by marine currents, with protective fruit casings increasing the likelihood of successful establishment by safeguarding the seed during dispersal and deposition (Celdrán et al., 2013; Celdrán et al., 2015; Balestri et al., 2017; Guerrero-Meseguer et al., 2018). Taken together, these sexual and clonal strategies explain how P. oceanica combines very slow growth with remarkable persistence and the capacity to colonise new areas when favourable environmental conditions occur.

## 7. Ecological Roles

### 7.1 Biodiversity hotspot

Scientific reviews and ecological surveys confirm that P. oceanica meadows host high biodiversity, acting as crucial nursery habitats and refuges for numerous marine organisms, including fish, molluscs, and invertebrates. They contribute significantly to Mediterranean endemism by supporting species that are rare or absent outside these seagrass beds (Balestri et al., 2017; Cantasano, 2023). Together, these findings highlight P. oceanica meadows as keystone ecosystems whose structural complexity and longevity underpin both local species richness and broader patterns of marine diversity in the Mediterranean.

### 7.2 Ecosystem services

Research has documented that Posidonia meadows stabilise coastal sediments and protect shorelines from erosion, and they are recognised as important carbon sinks, storing large amounts of organic carbon in both their biomass and underlying mattes, which helps to mitigate climate change. Meadows enhance primary productivity and act as buffers against ocean acidification by optimising carbonate cycling and trapping $CO_2$, and they improve water quality by trapping sediments and nutrients, thereby reducing turbidity and supporting healthier marine ecosystems (Balestri et al., 2017; Cantasano, 2023). Collectively, these services emphasise the dual role of P. oceanica as a geomorphological engineer and a regulator of biogeochemical processes, providing strong justification for its prioritisation in coastal conservation and management strategies.

## 8. Conservation Challenges

Peer-reviewed studies and environmental assessments highlight the vulnerability of P. oceanica meadows to multiple anthropogenic stressors. Coastal development leads to direct habitat destruction, eutrophication from nutrient loading degrades water quality, and climate change imposes additional physiological stress on meadow health. The extremely slow annual growth rate of P. oceanica (2–6 cm year$^{1-}$) further emphasizes the limited capacity of these meadows for rapid natural recovery following disturbance. In addition, reports estimate that more than 34% of P. oceanica meadow area has been lost in recent decades, underlining the urgency of effective conservation action. Recent scientific literature and policy analyses also indicate that regional and European legal frameworks, including the Habitats Directive, play a crucial role in the protection and restoration of these habitats (Balestri et al., 2017; Cantasano, 2023). Taken together, these findings show that the ecological importance of P. oceanica is matched by a high level of vulnerability, making stronger protection, long-term monitoring, and better enforcement of conservation policies essential.

## 9. Physical Properties of P. oceanica

Bulk density values of P. oceanica residues remain notably low, well below the thresholds associated with substrate compaction, while particle density falls within ranges considered favourable for root development. Total pore space exceeds minimum recommended values and is accompanied by high air capacity, ensuring adequate gaseous exchange, which is particularly advantageous given the gradual decline of these parameters during crop cycles as a result of particle disaggregation and root expansion (Abad et al., 2001; Morel et al., 2007; Cocozza et al., 2011). Collectively, these findings indicate that properly processed P. oceanica residues possess physical characteristics suitable for use in growing media, particularly as partial substitutes for conventional peat-based substrates.

## 10. Chemical Properties of P. oceanica

Chemical characterization of P. oceanica residues reveals a lignocellulosic composition dominated by cellulose (35–45%), hemicellulose (20–30%), and lignin (20–25%), together with notable proportions of proteins (5–10%), lipids (2–5%), and ash (10–15%). These organic fractions confer structural stability and relatively slow biodegradability, which support the use of P. oceanica residues as durable components in composting mixtures and soilless substrates (Cocozza et al., 2011; Astudillo et al., 2021). Taken together, this compositional profile suggests that P. oceanica biomass combines mechanical persistence with biochemical complexity, making it relevant not only for substrate formulation but also for downstream applications involving nutrient recycling and bioactive compound recovery. Table 1 shows the comparative chemical composition of P. oceanica biomass reported in previous studies.

**Table 1. Comparative chemical composition of P. oceanica biomass reported in previous studies**

| Component | Reported Range (% DW) | Main References | Importance |
|---|---|---|---|
| **Cellulose** | 35–45% | Cocozza et al., 2011; Astudillo et al., 2021 | Structural stability; substrate durability |
| **Hemicellulose** | 20–30% | Rencoret et al., 2020; Lefebvre et al., 2023 | Carbon source for microbial activity |
| **Lignin** | 20–25% | Rencoret et al., 2020; Bruno et al., 2023 | Mechanical resistance; slow decomposition |
| **Ash** | 10–15% | Bruno et al., 2023; Souii et al., 2023 | Mineral content; salinity indicator |
| **Phenolics** | Variable (0.5–5%) | Benito-González et al., 2019; Errayes et al., 2025 | Bioactive properties; antimicrobial activity |
| **Nitrogen** | 0.5–1.5% | Castaldi & Melis, 2010; Mininni et al., 2014 | Nutrient availability; C:N ratio determinant |
| **Potassium** | 1–2% | Bruno et al., 2023 | Macronutrient for plant growth |
| **Calcium** | 1–1.5% | Bruno et al., 2023 | Structural component; pH buffering |

Variability is noted in the chemical composition of P. oceanica biomass in Table 1, where it can be seen how it varies depending on factors like the type of tissue (leaves, rhizomes, or beach cast), place of collection, seasonality, and method of analysis used (Bruno et al., 2023; Rencoret et al., 2020). Nonetheless, it is worth noting that the lignocellulosic matrix (comprising cellulose, hemicellulose, and lignin) remains dominant, which makes it a suitable candidate for incorporation into the growing media and compost mixtures (Cocozza et al., 2011; Souii et al., 2023). The high variability in the concentration of phenolics (0.5-5% DW) suggests the need for standardization of extraction procedures due to the sensitivity of the phenolic profile to environmental conditions and aging of tissues (Botes et al., 2025; Errayes et al., 2025).

## 10.1 Elemental and Nutrient Profile

Carbon content predominates at 40–45%, supporting high organic matter stability, whereas nitrogen levels of 0.5–1.5% result in C:N ratios ranging from 40:1 to 60:1, indicative of moderate mineralisation potential suitable for blended fertilisers. Macro-elements include potassium (1–2%), calcium (1–1.5%), and magnesium (0.3–0.6%), with trace micronutrients such as iron and zinc enhancing the nutritional value of P. oceanica residues for horticultural applications. Phenolic compounds, including zosteric acid, chicoric acid and various flavonoids, contribute antifungal and biostimulant properties, aligning this biomass with applications in plant pathology control and crop performance enhancement (Cocozza et al., 2011; Bruno et al., 2023). The main differences in ash content, C:N ratio, and macro- and micro-nutrient concentrations between beach-cast residues, roots and leaves are summarised in Figure 3–Figure 8. Taken together, these elemental and phenolic profiles suggest that P. oceanica can act simultaneously as a structural component of growing media and as a source of bioactive metabolites relevant for integrated nutrient and disease-management strategies.

## 10.2 Antioxidant Properties

Several studies show that P. oceanica extracts possess strong antioxidant capacity attributable to their phenolic compounds and polysaccharides. For example, different solvent extracts (acetone, methanol, ethanol) of P. oceanica leaves have demonstrated notable reductions in oxidative stress through effective scavenging of free radicals

(Benito-González et al., 2019; Astudillo et al., 2021; Errayes et al., 2025). Overall, the consistency of high antioxidant indices across multiple extraction protocols supports the view that P. oceanica represents a promising source of natural antioxidants for food preservation, cosmetic formulations and plant stress-mitigation products.

### 10.3 Antimicrobial Properties

P, oceanica extracts have demonstrated antibacterial activity against pathogens such as Staphylococcus aureus and Enterococcus faecalis, as well as antifungal effects against Fusarium oxysporum and other crop-related fungi. Experimental work repeatedly highlights robust inhibitory activity of P. oceanica-based extracts, confirming their potential as biopesticides for controlling soil and crop pathogens or as antimicrobial agents in food systems (Kouki et al., 2012; Berfad et al., 2013; Berfad & Alnour, 2014; Piva et al., 2017; Benito-González et al., 2019; Ozbil et al., 2024). The semi-quantitative antibacterial responses of the different solvent extracts are illustrated in Figure 9, and the antifungal activity of aqueous P. oceanica extracts against Pythium spp. and Aspergillus flavus at different concentrations is shown in Figure 10. Across these studies, a consistent pattern emerges: leaf and rhizome extracts obtained with relatively non-polar or hydroethanolic solvents tend to show the strongest inhibition against Gram-positive bacteria such as Staphylococcus aureus and plant-pathogenic fungi, whereas activity against Gram-negative species is often weaker or highly protocol-dependent. This suggests that phenolic-rich fractions targeting membrane integrity and key enzymes are central to the antimicrobial profile of P. oceanica, while methodological differences in solvent polarity, tissue selection and extraction conditions largely explain discrepancies between studies rather than fundamental contradictions in the intrinsic bioactivity of the species.

Figure 4 gives an overview of the primary categories of bioactive compounds and their biological activities found in the P. oceanica biomass. Phenols, mainly zosteric acid, chicoric acid, and flavonoids (quercetin, kaempferol), have been studied most widely in P. oceanica (Benito-González et al., 2019; Bruno et al., 2023; Botes et al., 2025). It has been shown that they are strong antioxidants due to their ability to act on free radicals and demonstrate antimicrobial potential towards

Gram-positive bacteria and phytopathogenic fungi (Berfad & Alnour, 2014; Errayes et al., 2025). Tannins and terpenoids can be mentioned among the bioactive compounds, implying the multicomponent mechanism of their action (Souii et al., 2023). The recent results of metabolomics studies have demonstrated great differences in the phenolic profiles depending on the type of tissues, seasons of collection, and stress conditions (Pinna et al., 2026; Mollo et al., 2026). It means that the optimal times of collection and extraction should be used for obtaining bioactive compounds. Due to their structural diversity, bioactive compounds of P. oceanica can serve as a basis for the creation of natural biopesticides, biostimulants for plants, and pharmaceutical preparations (Yildirim et al., 2025).

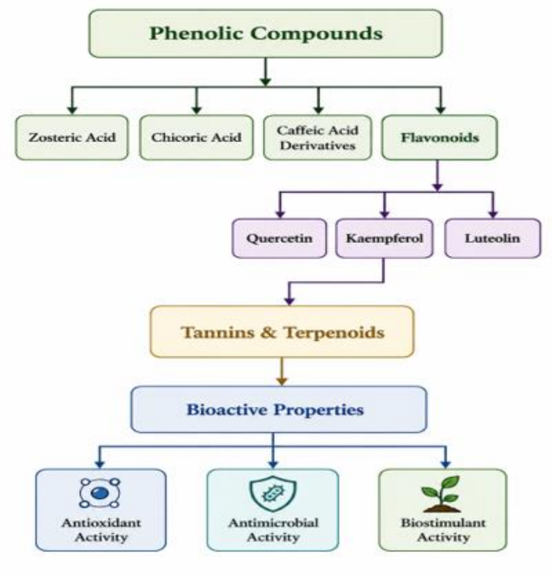


**Figure 4. Bioactive compounds identified in P. oceanica biomass**

### 10.4 Bioindicator function

P. oceanica accumulates heavy metals in its tissues, making it a sensitive indicator of marine pollution and stress-related changes in phenolic compound composition (Errayes et al., 2025). This dual role as both a habitat-forming species and a chemical sentinel reinforces its value for long-term monitoring of coastal water quality and for linking contaminant exposure with shifts in secondary metabolism.

## 11. Agricultural Applications

P. oceanica has been traditionally utilized in agriculture as organic amendments, fodder, and compost due to its nutrient richness and beneficial effects on soil properties and crop productivity, findings corroborated by multiple scientific studies and reviews. Key strengths include its provision of essential macro and micronutrients, soil structure enhancement through reduced bulk density and improved water retention, promotion of beneficial microbiota, and increased crop yield parameters such as fresh weight, leaf area, and chlorophyll content (Castaldi et al., 2002; Mininni et al., 2014; D'Imperio et al., 2021). The agronomic implications of using P. oceanica are summarised in Figure 11 and Figure 12, which respectively depict Brassica microgreen yield on P. oceanica substrates and the germination responses of cucumber and tomato to aqueous extracts. Additionally, composting seagrass residues addresses coastal waste management while supplying sustainable resources (Emadodin et al., 2020; Souii et al., 2023; Zobiri, 2024). However, several limitations must be addressed for optimal application. Elevated salinity (Na, Cl) and potential heavy metal contamination from polluted coastal zones necessitate thorough washing and processing to prevent phytotoxicity (Balestri et al., 2009; D'Imperio et al., 2021). Nutrient composition, physical properties, and efficacy exhibit significant variability depending on collection site, season, processing methods, and local pollution levels (Leriche et al., 2006; Cocozza et al., 2011; Ramos-Esplá et al., 2025). Finally, while benefits are well documented at small pot and field scales with limited Mediterranean crop species, large scale agronomic performance and longterm soil health impacts remain underexplored (Mininni et al., 2014; Emadodin et al., 2020; Zobiri, 2024).

Overall, pot and greenhouse trials converge on the view that P. oceanica residues can safely replace only a fraction of peat in growing media, with agronomic benefits—improved yield, nutrient status, and substrate structure—appearing at low substitution rates but declining or inverting when salinity and C:N ratios are not adequately managed. The strong influence of washing intensity, composting strategy, and residue origin on crop responses underscores that the agronomic potential of P. oceanica is conditional rather than universal, and that standardized pretreatment and dosing guidelines are essential before large-scale adoption in Mediterranean horticulture (Figure 4).

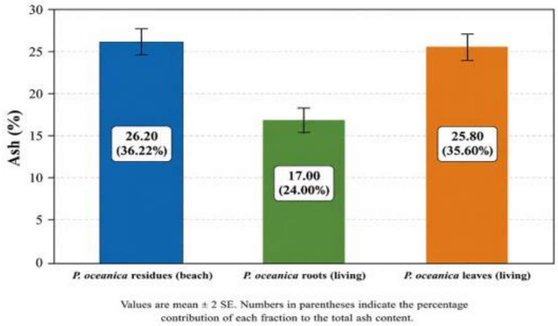


**Fig 4. Ash content of P. oceanica beach cast residues, living roots and leaves, expressed as percentage of dry weight (% DW), as reported by Bruno et al. (2023).**

Figure 5 shows the comparison of the carbon to nitrogen (C/N) ratio in different types of P. oceanica biomass, such as beach cast debris, live roots, and live leaves. The C/N ratio was highest in beach cast debris, which amounted to 63.0, suggesting that it consists of high amounts of carbon and has a slow decomposition rate and is best suited to be used as a compost and soil amendment material. On the other hand, live roots (27.7) and live leaves (25.0) were found to have a low C/N ratio, meaning that they have a relatively higher content of nitrogen and fast degradation rate.

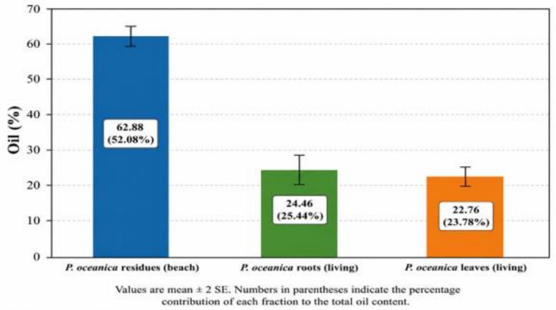


**Figure 5. C/N ratio of P. oceanica beach cast residues, living roots and leaves, summarized from Bruno et al. (2023). Error bars indicate ±2 SE.**

Figure 6 illustrates the distribution of total carbohydrate (CH) content among different P. oceanica biomass fractions, including beach-cast residues, living roots, and living leaves. Living leaves exhibited the highest total carbohydrate content (45.8%), reflecting their active photosynthetic function and accumulation of structural and non-structural carbohydrates. Beach-cast residues showed an intermediate carbohydrate level (33.4%), indicating that a substantial proportion of polysaccharides is retained after deposition on the shoreline despite exposure to environmental degradation. In contrast, living roots contained the lowest carbohydrate content (15.9%), consistent with their primary role in anchorage and nutrient transport rather than carbohydrate storage. Overall, these variations demonstrate that biomass fraction strongly influences carbohydrate composition, which has important implications for selecting suitable feedstocks for compost production, bio-based materials, and biorefinery applications.

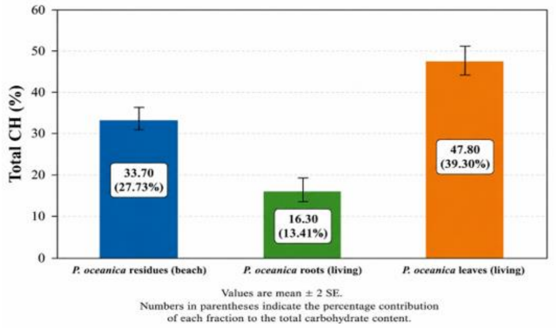


**Figure 6. Total calcium (Ca) content of P. oceanica beach cast residues, living roots and leaves (g kg⁻¹ DW), summarized from Bruno et al. (2023). Error bars indicate ±2 SE.**

The distribution of total magnesium (Mg) concentration in different biomass fractions of P. oceanica, such as beach-cast residues, living roots, and living leaves, is shown in Figure 7. As can be seen from the collected information, living leaves possess the highest magnesium concentration (10.0) that accounts for about 45.45% of total Mg, while beach-cast residues demonstrate an intermediate concentration (7.0; 31.82%). The lowest magnesium concentration was found in living roots (5.0; 22.73%). Such a distribution of the element under consideration can be explained by the physiological significance of magnesium as a central atom in chlorophyll molecules and participation of this element in photosynthesis, enzymes activation, and carbohydrates metabolism. As follows from the results obtained, the presence of high magnesium concentration in beach-cast residues indicates that these materials can serve as a good source of minerals even after deposition on shorelines.

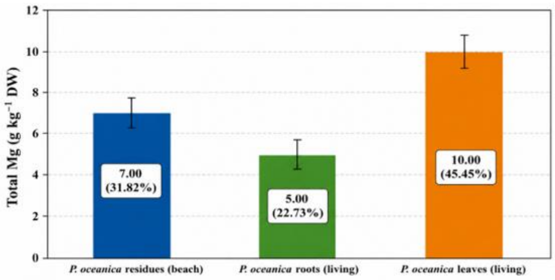


**Figure 7. Total magnesium (Mg) content of P. oceanica beach cast residues, living roots and leaves (g kg⁻¹ DW), summarized from Bruno et al. (2023). Error bars indicate ±2 SE.**

Figure 8 shows the comparative values of total Sodium (Na) concentration between various fractions of P. oceanica biomass such as beach-cast residues, living roots, and living leaves. According to the compiled data from literature, beach-cast residues possess the highest concentration of Sodium (20.7), making up around 51.88% of the total Na, while living roots (15.2; 38.10%) and living leaves (4.0; 10.03%) have lower concentrations of Na. The higher concentration of Na in beach-cast residues can be attributed to their exposure to coastal sediments and seawater, which help accumulate mineral particles and metal deposits in the course of staying on the shore. On the contrary, relatively low concentration of Na in living leaves is the result of metabolic processes and regulation of Na uptake in metabolizing plant parts. Based on the obtained results, beach-cast residues can be considered Na -rich source for compost production.

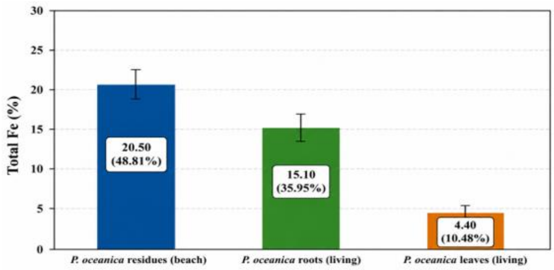


**Fig 8. Total sodium (Na) content of P. oceanica beach-cast residues, living roots and living leaves (g kg⁻¹ DW), summarized from Bruno et al. (2023). Error bars indicate ±2 SE.**

Figure 9 illustrates the total iron (Fe) concentration (mg kg⁻¹ DW) measured in various biomasses of P. oceanica, namely, beach-cast residues, living roots, and living leaves. Based on the analysis of the literature data, it can be seen that beach-cast residues contain the highest iron concentration (4,758 mg $kg^{-1}$ DW), comprising approximately 61.90% of the total Fe concentration, compared to living roots (2,438.4 mg $kg^{-1}$ DW; 31.72%), and living leaves (489.9 mg $kg^{-1}$ DW; 6.37%) with the lowest iron content among all studied samples. The increased iron concentration in beach-cast residues is probably related to the prolonged contact of this material with marine sediments and mineral deposits of the coast. As a result, the process of iron particles adsorption and retention is intensified. At the same time, the decreased Fe concentration in living leaves can be explained by strict regulation of iron homeostasis due to the necessity to perform photosynthesis without oxidative stress.

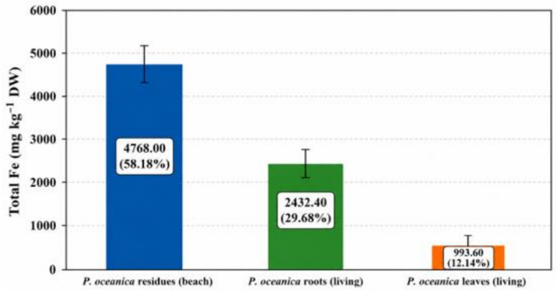


**Figure 9. Total iron (Fe) content of P. oceanica beach cast residues, living roots and leaves (mg $kg^{-1}$ DW), summarized from Bruno et al. (2023). Error bars indicate ±2 SE.**

The comparison of antimicrobial activities of various solvents' extracts of marine biomass against six pathogens such as Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli, Klebsiella pneumoniae, Salmonella typhi, and Proteus mirabilis is shown in Figure 10. As can be seen from the analysis of the gathered literature data, there exists a noticeable difference in the antimicrobial activity depending on the solvent used. Ethyl acetate extracts demonstrate the highest antibacterial activity in respect to all studied microorganisms, cyclohexane and ethanol extracts possess moderate activity, while acetone and chloroform extracts have weaker inhibitory action. Gram-positive S. aureus was found to be relatively sensitive to all types of solvents, while Gram-negative bacteria have demonstrated different sensitivity due to specific cell wall features. All of these results underline the important impact of solvent polarity on the isolation of phenols and flavonoids that are responsible for antimicrobial activity of marine biomass. Thus, the choice of proper solvent is critical in order to achieve maximum benefits from the use of P. oceanica phytochemicals in various industries.

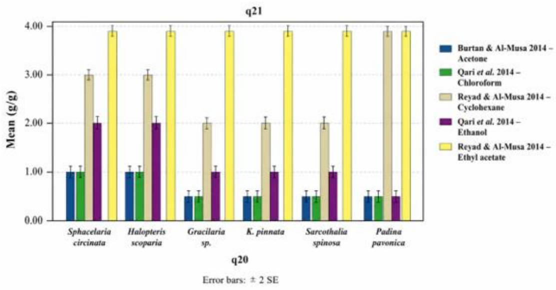


**Figure 10. Semi quantitative antibacterial activity of different solvent extracts of P. oceanica against selected bacterial strains, summarized from Berfad & Alnour (2014). Activity was scored as 0 = no reaction, ± = unclear result, + = weak, 2+ = good and 3+ = strong response.**

Figure 11 shows the antimicrobial activity of aqueous extracts of P. oceanica against some phytopathogenic fungi at various extract concentrations. Based on the literature review data, it can be concluded that the strongest antimicrobial effect was provided by aqueous extract with respect to Pythium spp. (approximately 50% growth inhibition at 5% extract concentration), while the antifungal activity towards Aspergillus flavus was relatively constant and amounted to about 33-34% within a range of extract concentrations from 5% to 15%. Thus, according to the presented results, the antifungal activity of extracts from P. oceanica is highly species-specific and depends on the cell wall composition of pathogen, its metabolic characteristics, and sensitivity to phytochemicals. The observed antifungal activity is likely caused by the presence of such active components as phenolic acids, flavonoids, and tannins that interfere with membrane integrity, enzyme activity, and lead to oxidative stress development in the fungal cells.

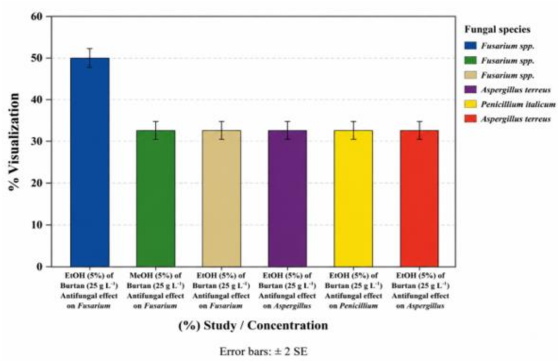


**Figure 11. Antifungal activity of aqueous P. oceanica extracts against Pythium spp. and Aspergillus flavus at different concentrations, summarized from Berfad et al. (2015). Bars represent the percentage of mycelial growth inhibition reported by the original authors.**

The impact of the various formulations of P. oceanica substrate materials on the average height (stem + roots) of seedlings is shown in Figure 12 relative to the peat-only control. As per the compilation of literature results, the partial replacement of peat by P. oceanica material resulted in better plant growth in most cases; however, the degree of improvement depended on the type of material and amount used. Substrates with P. oceanica fibers had the highest impact on increasing seedling height; those with 2.5% fiber addition (97.5% peat + 2.5% fibers) showed the maximum value of mean height (3.75 cm). Substrates with 5.0% and 7.5% biomass addition also exceeded the control values, which shows that fiber materials have good physical properties such as proper aeration, water holding ability, and root penetration. Likewise, leaves resulted in an incremental growth of plants with increasing biomass content; the 7.5% leaf amendment had the highest impact among all leaf-containing substrates (3.60 cm). Thus, these results show that properly formulated P. oceanica growing media can be effective substitutes for peat.

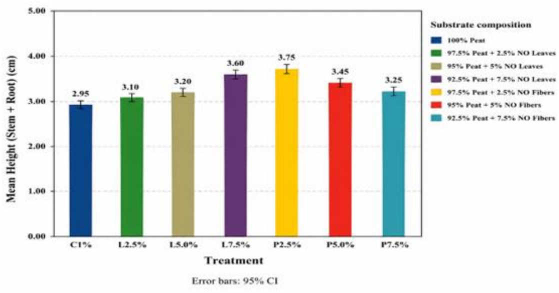


**Figure 12. Mean yield of Brassica microgreens (Mizuna + Rapini) grown on peatbased substrates amended with different proportions of P. oceanica leaves or fibers, summarized from D'Imperio et al. (2021).**

The impact of various P. oceanica extract concentrations on germination efficiency and early seedling vigor indices such as RSG, RRG, GI, NRGI, and RER is shown in Figure 13. According to the data summarized from literature, seeds without any treatment (control) demonstrated the highest values in all investigated indices and were used as the reference point for the germination efficiency. Within the groups of extract-treated seeds, the best performance was obtained with 0.05 concentration, especially due to high values of the relative root growth and germination index close to the values for the control seeds. In contrast, higher concentration (0.10) of the extract reduced several germination indices, especially residual radicle elongation index, indicating the inhibitory effect of higher extract concentration on the germination efficiency. Based on these results, it can be concluded that P. oceanica extracts exhibit concentration-dependent biological activity, with appropriate application concentration preserving or stimulating germination efficiency while excessive extract concentrations decreasing seed vigor due to the increased amounts of phenolics and secondary metabolites. Overall, the results support the applicability of properly optimized P. oceanica extracts as natural biostimulants for seeds.

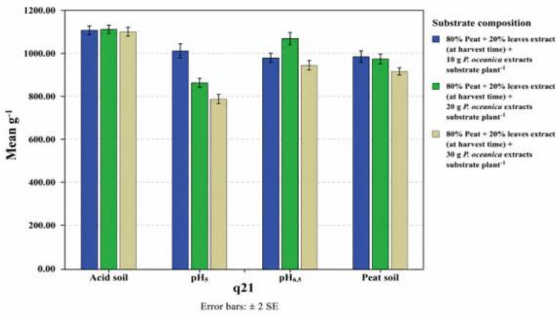


**Figure13. Germination response of tomato seeds to different concentrations of aqueous P. oceanica extracts, summarized from Ferrández-Gómez et al. (2023).**

As seen in the comparative analysis shown in Table 2, although there is a lot of potential in using the P. oceanica biomass in many areas of agriculture, its current state of readiness remains experimental. The composting and growing media applications have had much of the attention from researchers, resulting in good results in growing various horticultural crops in Mediterranean conditions (Mininni et al., 2014; D'Imperio et al., 2021; Zobiri, 2024). Nevertheless, there is still a need to overcome some limitations, including salinity, high C:N ratio requiring supplementing, potential accumulation of heavy metals, and dose-dependent phytotoxicity (Balestri et al., 2009; Bruno et al., 2023). The biostimulant application shows promising antimicrobial and antioxidant properties, but there is still a need to establish the protocol for extracting them and validate their effects on the fields (Yildirim et al., 2025). The reason why the state of readiness for the mulching application is relatively low is that little attention has been paid to it by researchers.

**Table 2. Comparison of agricultural applications of** P. oceanica **biomass**

| Application | Benefits | Limitations | Readiness Level | Key References |
|---|---|---|---|---|
| Composting | Nutrient enrichment; soil structure improvement; waste management | High C:N ratio; salinity; requires co-composting with N-rich materials | Moderate (pot/greenhouse scale) | Castaldi & Melis, 2010; Mininni et al., 2014; Zobiri, 2024 |
| Growing Media | Peat substitution; enhanced water retention; reduced bulk density | Salinity; heavy metal risk; variable quality | Low-medium (limited crops tested) | D'Imperio et al., 2021; Cocozza et al., 2011 |
| Mulching | Weed suppression; moisture conservation; erosion control | Slow decomposition; aesthetic issues; salt accumulation | Low (limited studies) | Emadodin et al., 2020 |
| Biostimulant | Antimicrobial activity; antioxidant properties; plant stress mitigation | Dose-dependent phytotoxicity; extraction variability | Low (experimental) | Ferrández-Gómez et al., 2023; Yildirim et al., 2025 |
| Soil Amendment | Organic matter addition; improved microbial activity | Nutrient imbalance; high sodium; potential contamination | Moderate | Castaldi & Melis, 2002; Souii et al., 2023 |

## 12. Discussion

Overall, most studies agree on the structural role of P. oceanica rhizomes and leaves in stabilizing the seafloor and supporting biodiversity, while converging on the view that its biomass contains diverse bioactive compounds whose extraction efficiency and chemical profile strongly depend on the method used. Taken together, this body of work highlights a dual ecological and biotechnological significance for the species, linking its capacity to engineer coastal habitats with its potential to provide phenolic-rich extracts for antimicrobial and bioindicator applications.

Most studies agree on the structural role of rhizomes and leaves in stabilizing the seafloor and supporting biodiversity (Gerakaris et al., 2021), P. oceanica biomass contains diverse bioactive compounds; extraction efficiency and profile depend on the method (Berfad &Alnour 2014; Abdulrraziq & Salih 2020), There is broad agreement on the antioxidant, antibacterial, antifungal and bioindicator properties of its phenolic content, supporting uses in environmental conservation and potential biotechnological applications. (Berfad et al., 2013; Berfad & Alnour, 2014; Errayes et al., 2025).

Together, the body of evidence indicates that the ecological and biotechnological importance of the P. oceanica biomass makes it an extremely strategic biomass for sustainable agriculture in the Mediterranean. Nevertheless, large variability in the chemical and bioactive composition, as well as the agronomic efficacy of the biomass, highlights the highly contextual character of the biomass utilization. Consequently, detailed research accounting for the relevant spatial and temporal aspects is absolutely necessary to provide effective biomass processing and application guidelines for commercial implementation.

While numerous studies have examined the leaf chemistry of P. oceanica, far fewer have investigated root and rhizome compositions, particularly lignin and total phenolic contents (Errayes et al., 2025). Several reports demonstrate substantial antimicrobial activity, especially against S. aureus and Candida spp., though the potency and spectrum vary by extraction method, tissue type (leaves versus rhizomes), and concentration. Activity against Gram negative bacteria such as E. coli and P. aeruginosa has been negligible in some studies but moderate in others. These effects are mechanistically linked to phenolic acids and flavonoids, which disrupt microbial membranes and inhibit key enzymes (Berfad & Alnour, 2014; Abdulrraziq & Salih, 2020; Messina et al., 2021; Souii et al., 2023). Phenolic content in P. oceanica also varies with environmental stressors, pollution, and geographic location, underscoring its context dependent nature (García-Márquez et al., 2022). The effects of light and temperature on chlorophyll content in P. oceanica remain debated; García-Márquez et al. (2022) reported increases under high light at ambient temperatures, while broader evidence suggests minimal or stressor dependent impacts. Spatial and historical distribution data reveal discrepancies in meadow decline rates, primarily attributed to climate change and anthropogenic pressures (Telesca et al., 2015; Hendriks et al.,2017; Ruocco et al.,2019; Stipcich et al.,2022).

As a whole, all the above data indicate that the phenol-containing extract from P. oceanica is consistently characterized by its antibacterial and antifungal properties. Nevertheless, the efficiency of the extract is quite variable depending on the extraction technique, biological tissue used for the extract preparation, and other conditions, which means that standardization procedures are required for the practical use of this extract. Consequently, further studies should be focused on the development of optimized protocols of the extract production (Botes et al., 2025; Jaroslava et al., 2026).

Recent chemical characterizations converge on the view that the transition from living tissues to beach-cast residues profoundly alters the agronomic profile of P. oceanica biomass. Bruno et al. (2023) showed that stranded residues are more mineralized than roots and leaves, with higher ash content, lower organic C and total N, and consequently higher C/N ratios, in agreement with earlier descriptions of carbon-rich, nitrogen-poor, saline residues and the need for co-composting with N-rich materials to obtain balanced composts (Castaldi & Melis, 2010; Cocozza et al., 2011; Mininni et al., 2013). The enrichment of Fe, Mo and B in residues, contrasted with higher Ca, Mg, Mn and Zn in leaves, further supports the idea that micronutrients partition differentially between aging structural tissues and metabolically active organs, while consistently low phenolic and carbohydrate levels in residues help explain why bioactivity studies focus on fresh leaves and rhizomes rather than on aged banquettes (Cocozza et al., 2011; Di Mola et al., 2021; Llorent-Martínez et al., 2021; Bruno et al., 2023).

Overall, the literature reviewed here seems to indicate that residues of P. oceanica may be used as effective partial substitutes of peat for soilless plant growing media of crops which have a moderate tolerance to salinity. Nevertheless, taking into account both the dose dependency of plant response to P. oceanica treatment and significant variation in performance of the substrates among different studies, one should admit that it is necessary to determine empirically safe rates of P. oceanica application to different crops in specific growing systems (Yildirim et al., 2025; Bacchetta et al., 2024).

In line with this chemical profile, multiple studies report strong antibacterial and antifungal activities for phenolic-rich extracts obtained with organic or optimized solvents, particularly against S. aureus, P. aeruginosa, Pythium spp. and A. flavus (Ayad Berfad & Alnour, 2014; Berfad et al., 2015; Inglese et al., 2019; Kose et al., 2024). The predominance of cyclohexane and ethanol fractions in the semi-quantitative scores summarized from Berfad and Alnour (2014) is broadly consistent with work showing that solvent polarity and extraction conditions strongly influence total phenolic content and antimicrobial potency, even though some studies highlight only moderate activity against certain Gram-negative bacteria or greater efficacy of aqueous and hydroethanolic preparations, reflecting differences in plant organ, collection site and extraction protocols rather than contradictions in the intrinsic bioactivity of P. oceanica (Inglese et al., 2019; Zafeiria et al., 2025).

From an agronomic perspective, greenhouse trials and germination assays indicate that P. oceanica residues can partly replace peat in growing media and that aqueous extracts can act as biostimulants or mild inhibitors depending on dose and crop species. Brassica microgreens tolerated relatively high proportions of P. oceanica residues and reached maximal yields at low medium substitution rates, whereas excessive inclusion or high extract concentrations tended to depress growth, especially in sensitive species such as cucumber (Castaldi & Melis, 2010; Mininni et al., 2014; D'Imperio et al., 2021; Ferrández-Gómez et al., 2023). Overall, the literature supports a dual role for P. oceanica as a source of antimicrobial metabolites and as a component of sustainable substrates, provided that its high C/N ratio, salinity and dose-dependent phytotoxicity are carefully managed through appropriate processing, blending and application rates.

A comparative analysis of the data presented by Mediterranean countries demonstrates the notable regional differences in both the quality of biomass and research directions. Research carried out in the western part of the Mediterranean region (Spain, France, Italy) is mostly associated with structural analysis and application of biomass as growing media (Cocozza et al., 2011; Mininni et al., 2014; D'Imperio et al., 2021; Bruno et al., 2023), while in the southern Mediterranean region (Libya, Tunisia, Algeria) there is greater research attention to bioactive compounds profile and antimicrobial activity (Berfad & Alnour, 2014; Errayes et al., 2025; Khemici, 2024).

A comparative analysis of different methods of extraction of bioactive compounds shows that the best yields of phenolics and antimicrobial activity can be achieved using organic solvents or hydroethanolic solutions, in particular from fresh leaves harvested during plant growth period (Benito-González et al., 2019; Astudillo et al., 2021). However, with increasing attention to "green" technologies of extraction such as ultrasound-assisted extraction and supercritical fluid extraction, the development of alternative methods with lower impact on environment becomes promising (Jaroslava et al., 2026; Mollo et al., 2026).

A comparison of the quality of the compost and the performance of the growing media shows that washing severity and co-composting with nitrogen-rich materials play the most important roles in determining their agronomic suitability (Castaldi & Melis, 2010; Mininni et al., 2014; Ramos-Esplá et al., 2025). Salinity in beach-cast debris, although a hindrance in the use of the biomass for sensitive crops, can be controlled through proper washing and mixing with less saline substrates (D'Imperio et al., 2021; Bruno et al., 2023).

## 13. Research Gaps

Even though there has been significant scientific interest in P. oceanica biomass over the last ten years, there are still some crucial knowledge gaps that limit its efficient valorization in sustainable agriculture.

## 14. Scale-Up and Field Validation

Most of the studies analyzing agricultural use of P. oceanica biomass have been carried out in the context of greenhouses and pots, with little application to field-level agriculture (Mininni et al., 2014; D'Imperio et al., 2021). There is an urgent need for multi-site, multi-year field trials to determine the effect of P. oceanica additions to soil on its fertility, crop growth, and ecosystems functioning under different Mediterranean agro-climatic conditions (Emadodin et al., 2020; Zobiri, 2024). Lack of such information creates a significant barrier to commercial application and regulation.

**15. Standardization of Extraction and Processing**

The significant variations in bioactive profiles that have been observed in various studies (see Tables 1-2) clearly indicate the necessity for standardization of extraction processes. There are huge differences between existing techniques in terms of polarity of solvent, temperature, time, tissue types used, and other factors. This makes inter-comparison and reproduction difficult (Berfad & Alnour, 2014; Astudillo et al., 2021; Errayes et al., 2025). Therefore, research on "green" extraction methodologies with use of eco-friendly solvents is a top research priority (Jaroslava et al., 2026; Mollo et al., 2026).

**16. Seasonal and Geographic Variability**

Although certain works have been conducted to determine the variability in terms of chemical components and biological activity, such systematic studies covering the entire Mediterranean region are still scarce (Leriche et al., 2006; García-Márquez et al., 2022; Bruno et al., 2023). It is crucial to investigate the impact of environmental conditions such as temperature, light, nutrition level, and the degree of pollution on the quality of biomass and bioactive compounds (Botes et al., 2025; Pinna et al., 2026).

**17. Heavy Metal Monitoring and Risk Assessment**

While the bio-indicator role of P. oceanica in terms of heavy metal pollution is important in the field of environmental monitoring, it poses a problem when applied in agriculture (Errayes et al., 2025; Ibraheem et al., 2022). The systematic evaluation of heavy metals in beach cast material at various sites in the Mediterranean, coupled with a full risk assessment of soil and crop contamination, is yet to be done properly (Balestri et al., 2009; Souii et al., 2023).

**18. Economic Feasibility and Life Cycle Assessment**

However, economic sustainability of valorizing P. oceanica biomass is largely unexplored. Conducting life-cycle assessment that takes into account the cost associated with harvesting, transportation, processing, and use of the product along with the environmental benefits (carbon capture, pollution control, etc.) is critical in proving its economic sustainability for commercialization purposes (Emadodin et al., 2020; Yildirim et al., 2025). It should be noted that no comparative economic analysis of using this natural alternative compared to conventional options has been conducted.

**19. Mechanistic Understanding of Bioactive Mechanisms**

Despite notable advances in the determination of phytochemical composition, the mechanism of action of both antimicrobial and biostimulant effects is not entirely known (Botes et al., 2025; Peruzzi et al., 2025). Molecular research into the specific mechanisms through which phenolic compounds prevent the proliferation of pathogens, regulate the plant immune response, and increase stress tolerance should be conducted in order to properly formulate products (Giulietti et al., 2025; Fubara et al., 2026). More work should be done on the importance of individual compounds compared to their synergistic effect within a complex mixture (Mollo et al., 2026).

**20. Rhizome and Root Biology**

In comparison with other tissues such as leaves and stranded plant materials, relatively few studies have been devoted to studying the chemical constituents of rhizomes and roots of P. oceanica despite the unique biological properties of the mentioned tissues (Bruno et al., 2023; Chen & Coughlan, 2026).

In light of the above, there is a need for concerted efforts on multi-disciplinary research to overcome the identified knowledge gaps and advance practical applications. The research gaps identified herein present important opportunities for future research that will help significantly in the valorization of P. oceanica biomass in climate-smart agroecosystems.

The future research directions in case of P. oceanica should be based on an integrated, multi-level framework that will focus on maximizing sustainable green extraction methodologies (like UAE and MAE) and their upscale from laboratory to pilot level production. It is crucial to use a biorefinery concept for the development of valorization routes at an industrial scale by using biomass for producing different types of products such as biopesticides, fiber composites, and bioenergy along with implementation of such systems within a circular economy model through life cycle and techno-economic analysis. In addition, the research efforts should involve climate change adaptation in order to examine the effects of stress conditions on biomass quality along with using advanced research tools such as metabolomics and transcriptomics for revealing mechanisms behind biosynthesis of various compounds.

Figure 14 illustrates a proposed roadmap of sustainable valorization of P. oceanica biomass by showing the step-by-step advancement in the research process from basic to applied research and commercial application in a circular bioeconomy context. In accordance with the proposed roadmap, the need for integration of molecular and mechanistic research with technological advancement and process optimization has been highlighted in order to make sure that the process of product development is based on scientific evidence and economically feasible (Botes et al., 2025; Jaroslava et al., 2026; Yildirim et al., 2025). Pilot scale production plays a crucial role in the transition phase as it provides validation of the efficiency of extraction, quality of the end-products, and process economics before moving on to the next level of commercialization (Flores-Félix, 2025; Mollo et al., 2026).

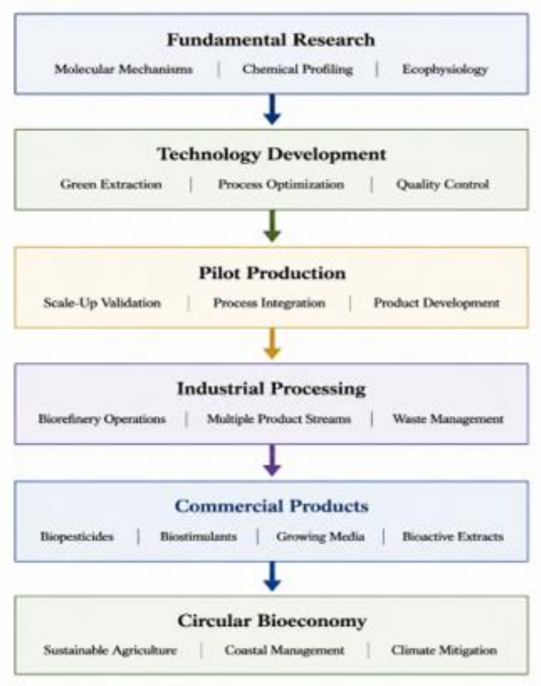


**Figure ١٤. Future roadmap for Posidonia oceanica biomass valorization**

The SWOT analysis described in Table 3 outlines a systematic evaluation of the key drivers affecting the use of biomass from P. oceanica for agricultural purposes. The SWOT analysis shows an optimal balance of strengths and opportunities in relation to the increasing need for sustainability and circularity in agriculture (Yildirim et al., 2025; Emadodin et al., 2020; Flores-Félix, 2025). At the same time, many weaknesses and threats, including variations in composition, salinity limitations, and effects of climate change, must be systematically analyzed and countered via scientific research and policy actions (Botes et al., 2025; Stipcich et al., 2022; Ibraheem et al., 2022). Such identification allows for developing a strategy for research investment and mitigation of threats related to sustainable valorization and preservation of the ecosystem of P. oceanica meadows (Souii et al., 2023; Zobiri, 2024).

**Table 3. SWOT analysis for** P. **oceanica biomass valorization in agriculture**

| Strengths | Weaknesses |
|---|---|
| **Renewable and abundant biomass resource** | Seasonal and geographic variability in composition |
| **Rich in bioactive phenolic compounds** | High salinity requiring pre-treatment |
| **Established lignocellulosic matrix for substrate applications** | Elevated C:N ratios limiting direct application |
| **Proven antimicrobial and antioxidant properties** | High moisture content increasing processing costs |
| **Carbon sequestration potential** | Variable heavy metal content requiring monitoring |
| **Coastal waste management synergy** | Limited shelf life without proper processing |
| Opportunities | **Threats** |
| **Circular economy integration** | Climate change impacts on meadow health and biomass quality |
| **Growing demand for sustainable agricultural inputs** | Marine pollution compromising biomass safety |
| **Peat substitution and reduced peat extraction** | Competition with established agricultural products |
| **Development of high-value bioactive products** | Regulatory constraints on marine resource utilization |
| **Biorefinery approaches for multiple product streams** | Economic viability challenges for commercial scale-up |
| **Policy support for sustainable resource management** | Public perception and acceptance barriers |
| **Climate-smart agriculture alignment** | Over-exploitation risks to natural meadows |

Figure 15 demonstrates a bio-economy-based valorization pathway for P. oceanica biomass involving harvesting, processing, and application. Such valorization is characterized by the recovery of several value-added materials through different processes following a sequence starting from the extraction of bioactive compounds for use in biopesticides and biostimulants to the use of lignocellulosic material for growth media and composts and ending with the production of energy and biochar from residual biomass (Souii et al., 2023; Yildirim et al., 2025; Jaroslava et al., 2026). This type of valorization pathway contributes to sustainable resource management since it increases resource efficiency and reduces the formation of waste, as well as meets the requirements of circular economy (Emadodin et al., 2020; Zobiri, 2024; Flores-Félix, 2025). Furthermore, the valorization process can bring additional value due to its contribution to sustainable agriculture and the solution of the problem of coastal waste accumulation and climate change mitigation (Fubara et al., 2026; Bacchetta et al., 2024).

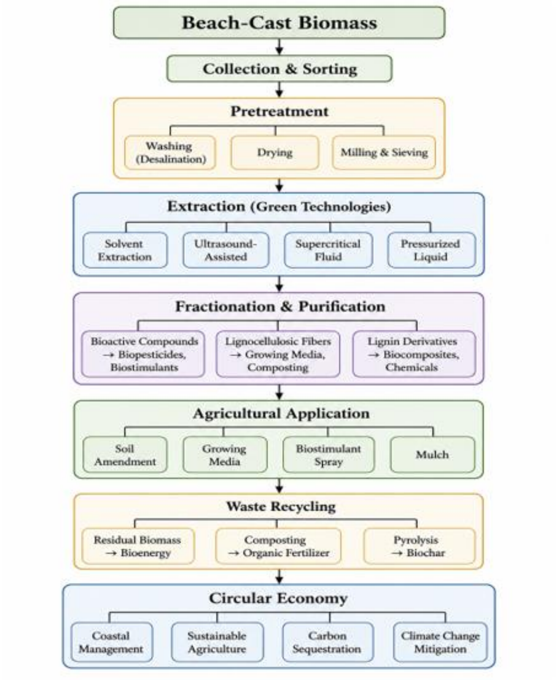


**Figure ١٥. Integrated biomass valorization pathway for** P. **oceanica**

*** Conclusions**

Overall, the studies reviewed here converge on the view that P. oceanica is a promising dual resource for sustainable agriculture, providing phenolic rich extracts with relevant antibacterial and antifungal activities and a mineral rich biomass that can partly substitute peat in growing media when carefully processed and applied at low medium rates. At the same time, its agronomic use is constrained by high C/N ratios, salinity and variable trace-metal contents in beach cast residues, as well as by the scarcity of long-term field trials and the lack of standardized protocols for biomass collection, pretreatment, extraction and dosing. Future research should therefore prioritise harmonised processing and extraction workflows, multi-site and multi-year experiments that define safe substitution rates and extract concentrations for different crops and soils, and mechanistic studies linking specific phenolic and terpenoid profiles to pathogen inhibition, phytotoxicity and plant growth responses, in order to unlock the full potential of P. oceanica within circular, climate smart agricultural systems, Collectively, this synthesis underscores P. oceanica as a strategically important yet still under-exploited resource, whose proper valorisation could simultaneously mitigate coastal biomass accumulation and contribute to more resilient, low input Mediterranean agroecosystems.

The move from laboratory-scale studies to industrial-level application is seen as the key challenge facing the potential of P. oceanica biomass utilization. Despite the scientific evidence supporting the promise offered by P. oceanica in various applications, there is need for considerable efforts in terms of developing processes, scaling up and markets (Yildirim et al., 2025; Flores-Félix, 2025). Actions needed for industrial development include:-

1-Demonstration facilities at pilot level that prove efficiency, quality and economic aspects of the process (Jaroslava et al., 2026)

2-Supply chain that connects coastal harvesting and processing to agriculture (Emadodin et al., 2020; Zobiri, 2024)

3-Quality control and certification of the products as safe and consistent considering the risks associated with heavy metal content and batch inconsistency (Bruno et al., 2023; Errayes et al., 2025)

4-Economic viability studies and LCA that prove economic case of adopting the technology (Emadodin et al., 2020; Souii et al., 2023)

5-Regulatory issues concerning the classification and marketing of P. oceanica-based products in agriculture (Yildirim et al., 2025)

The combination of the increasing demand for sustainable agricultural inputs, the necessity of decreasing peat exploitation, and the necessity of finding circular economy approaches provides a suitable environment for industrial investment in P. oceanica valorization (Flores-Félix, 2025; Fubara et al., 2026; Bacchetta et al., 2024). Nevertheless, in order to achieve this potential, it is necessary to engage all the participants including scientists, industries, and governmental policy-makers for solving various technical, economical, and regulatory issues. The creation of commercial products based on P. oceanica will not only increase resilience of the Mediterranean agroecosystems but will also show that marine biomass can be used as a sustainable source of agricultural inputs in the era of climate changes and resource shortage (Botes et al., 2025; Yildirim et al., 2025).

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