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Biovalorization of *Posidonia oceanica* waste biomass as a green approach toward a sustainable bioeconomy

Abstract

In the Mediterranean region, every summer the beaches have to be cleaned and millions of tons of *Posidonia oceanica* waste (POW) is often removed and not exploited. POW is mainly composed of fibrous materials consisting of cellulose and hemicellulose and lignin, as well as a significant percentage of ash and phenolic compounds. A solution to this ecological problem could be the valorization of this available and renewable biomass for the production of environmentally friendly industrial products. This mini-review focuses on the utilization of POW as a valuable biomass resource. In particular, seven POW valorization treatment approaches are discussed in this paper with a focus on bioenergy and biomaterials. The use of cleaner technologies can offer improved performance and an asset for contribution on sustainable POW management.

Keywords: *Posidonia oceanica*, biomass waste, valorisation, biotechnology, industrial products

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Abbreviations: NRPS, nonribosomal peptide synthetases; POW, *Posidonia oceanica waste*; PO, *Posidonia oceanica;* UMU, University of Murcia; CAZymes, carbohydrate-active enzymes

Introduction

Posidonia oceanica is the most abundant seagrass species in the Mediterranean basin, covering about 40,000km^2 of seabed and representing 60% of the seabed from 0 to 40m depth (Figure 1).[1] It plays important ecological roles as it participates in the oxygenation of seawater, protection of fauna and prevention of coastal erosion.[2,3] However, during its life cycle, *Posidonia oceanica* leaves detach from their stems and accumulate on the coast.[4,5] A moderately wide (1km) seagrass belt can produce more than 125kg of dry seagrass litter per meter of coastline each year.[1] Coastal municipalities must periodically remove this waste, which has a negative visual impact, in order to obtain the appropriate quality labels, which play a key role in attracting tourism.[6]

Figure 1 Localities of *Posidonia oceanica* waste along the mediterranean coasts.

Today, the accumulation of *Posidonia oceanica* residues are treated as wastes and landfilled without being used, resulting in huge losses of organic matter.[1] OPA was used in the past, in the construction industry as an insulating material; in the textile industry as a substitute for cotton, and as a raw material for the pulp and paper industry.[1,7,8] In recent years, new uses for *Posidonia oceanica* waste (POW) waste have been proposed (Figure 2). Some authors have reported the potential of POW (i) as a source of cellulose to strengthen conventional polymers; (ii) as a renewable and inexpensive adsorbent to remove heavy metals and organic compounds; (iii) as a suitable source of lignocellulosic fibers to produce a wide range of materials including textiles, paper and composites (Figure 2). The objective of this review is to highlight the different cost-effective and environmentally friendly recovery strategies for the effective reuse and recycling of POW.

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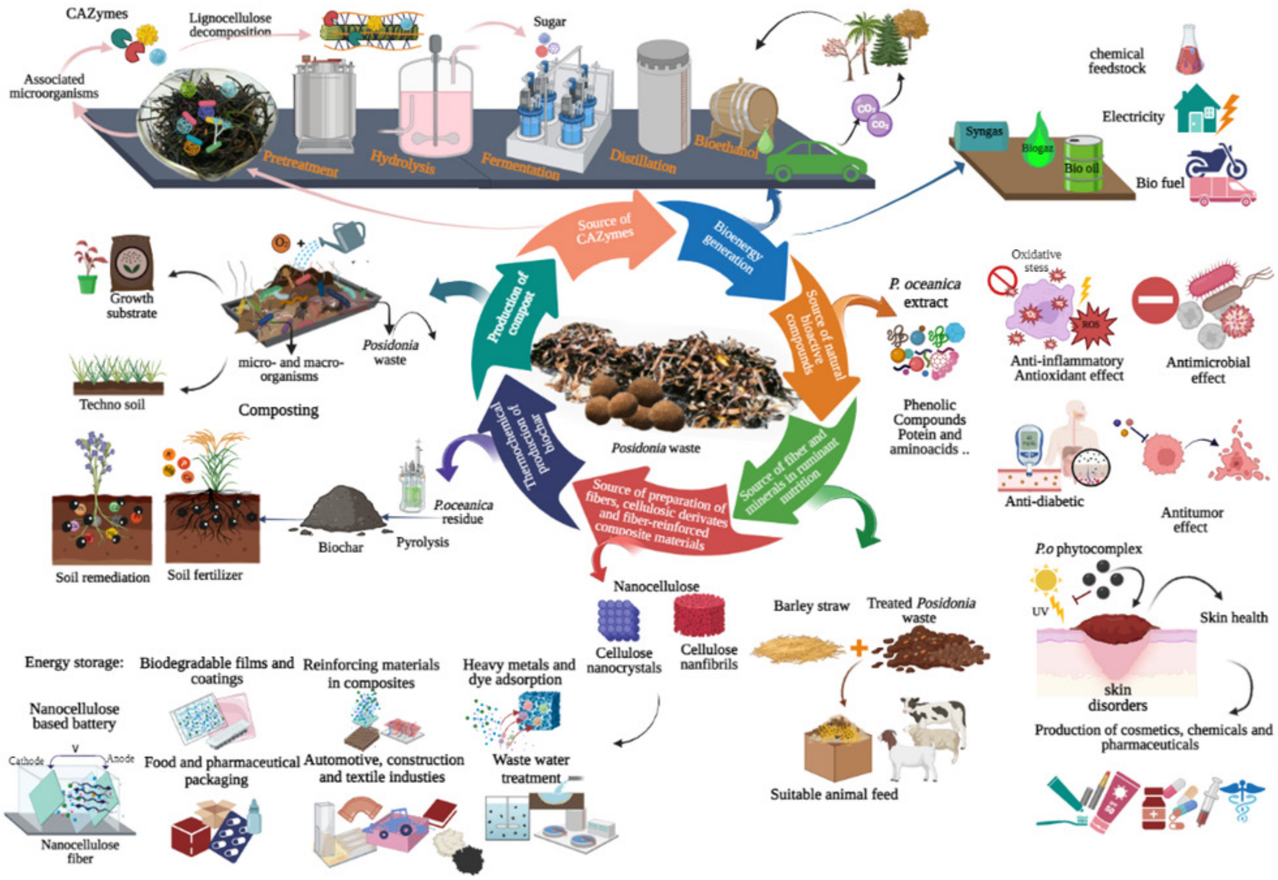

Figure 2 *Posidonia oceanica* waste valorization as a source of valuable biochemicals in circular economy.

Valorization of POW as a source of natural bioactive compounds

PO and POW have emerged as important reservoirs of bioactive compounds with immunostimulatory, antidiabetic, antioxidant, vaso-protective, antibacterial and antifungal activities.[5,9–19] They have been shown to contain partially known phenolic compounds such as some flavonoids and condensed proanthocyanidin tannins, as well as new compounds such as sesquiterpene. The main monophenols found are 4-hydroxybenzoic acid, 4-coumaric acid, cinnamic acid, caffeic acid, ferulic acid, myricetin, quercetin, isorhamnetin, kaempferol, gentisic acid, chicoric acid and vanillin. Recently, the Marine Protected Area of the Egadi Islands has launched a project (named Egadi Cosmesi) to use the active ingredients contained in *Posidonia oceanica* collected in the Egadi Islands in cosmetics.[20] Polyketide synthases (PKS) and multienzymatic nonribosomal peptide synthetases (NRPS) are active biomolecules, acting as antibiotics, immunosuppressants, antitumor agents, toxins, or siderophores are thus of significant interest to the pharmaceutical industry.[21] Although most PKS and NRPS are derived from soil samples, attention is turning to under-explored marine habitats such as POW which has a great potential as a source of new drugs and natural products.[22–24] The POW has also been valorized, through simple and ecological protocols, into bioactive multifunctional cellulosic aerogels to preserve the quality of fresh packaged foods. Bioactivity was conferred by incorporating hydrophilic and hydrophobic extracts produced from the same biomass POW. These aerogels showed exceptional water and oil sorption capabilities (1500-1900%) and a positive inhibition effect (23-91%) on the β-carotene bleaching assay. In addition, aerogels loaded with POW extracts were able to decrease lipid and oxymyoglobin oxidation in red meat after 10 days of storage.[25]

Valorization of POW as a source of preparation of fibers, cellulosic derivates and fiber-reinforced composite materials

The use of natural fibres to process novel composites has attracted growing interest given their abundance, low cost, low density, non-toxicity, biodegradability, high specific properties (modulus and strength), ease of fibre surface modification and low abrasiveness. In fact, several industries, such as automotive, construction and packaging, have focused their attention on the development of new materials filled with natural fibres. However, given their increasing demand for traditional uses (paper, textile, cellulose derivatives) and their potential incorporation into new material families, new sources of lingo-cellulosic fibres must be identified.[26,27] For this reason, several researchers have tested and evaluated the feasibility of using various agricultural wastes such as POW due to their low environmental impact and lack of dependence on fossil resources.[28] In recent years, many authors have investigated the use of POW fibers and cellulosic derivatives as: (i) a filler in potato starch-based films; (ii) a reinforcement in films based on high density polyethylene (HDPE), maleic anhydride grafted polyethylene/HDPE blend, polypropylene, polyvinyl alcohol, and wheat gluten; (iii) an adsorbent for removing metal-complexed dyes, phenols, ortophosphate ions or heavy metals as uranium (VI), chromium (VI), lead (II) (Table 1).[28–47] The improved mechanical and barrier properties, as well as the weakened water trapping ability, exhibited by the biocomposites containing POW fibers suggest a potential use of this waste, as a valuable renewable source for obtaining novel biodegradable materials alternative to the conventional plastics.[48]

Valorization of POW as a source of fiber and minerals in ruminant nutrition

POW can be used as a low-cost livestock feed. Researchers from the University of Murcia (UMU) are investigating the possibility of introducing *Posidonia oceanica* banquettes in animal feed.[8,48,49] According to these authors, the preparation of this animal feed is an inexpensive process that does not require specific treatment or chemicals. It only needs to wash. POW and left it to dry so that it can be used as livestock feed. The saving for the farmer will be considerable, because the OPW does not require treatment and its cost is very low (currently, about 0,10 euros per kilo). The Mucian-Granadine goats are fed a diet of POW and the experiment was repeated with sheep at the Estacion Agricola Experimental de Leon and with cows at the Universidad de Santiago. The main objective of the studies is to evaluate the effects of the introduction of POW as a substitute for barley straw in the diet of ruminants, evaluating first the effects of their addition on intake, digestibility and ruminal fermentation, and then evaluating these effects on metabolic profiles (energy and protein balances). These authors showed some potential for the use of POW as a source of fibrous forage to replace barley straw in ruminant rations, which could help optimize production costs without detrimental effects on animal production and health (Table 1).[8,48,49]

Valorization of POW for the thermochemical production of Biochar

Biochar is a stable, carbon-rich by-product (charcoal-like substance) produced by burning organic biomass in the complete absence (pyrolysis) or partial absence (gasification) of oxygen at temperatures ranging from 300 to 1000°C. Biochar is a promising amendment for biofilters to improve pathogen removal from stormwater runoff. It also promises to improve agriculture through soil remediation, due to its high organic carbon content, which implies high stability in soils and excellent nutrient retention properties. It is also involved in waste management due to its profitability and food security benefits. In addition, it contributes in climate change mitigation since biochar is carbon negative and therefore useful in removing carbon dioxide from the atmosphere. The production of biochar from POW by thermochemical processes has been recently studied and evaluated by many researchers.[50–53] As reported by Molto et al.,[53] the application of biochar derived from POW biomass as a soil remediator engenders improved soil properties, carbon sequestration, and plant growth. In addition, thermally treated POW has been proven effective as an adsorbent material for toxic metal ions or as a low-cost adsorbent material for phosphate removal from synthetic and real wastewater (Table 1).[52]

Valorization of POW for the production of compost

Castaldi and Melis[7] prepared a POW compost with sludge and woody residues. The evaluation of the physico-chemical parameters of the obtained compost showed a good carbon, nitrogen and phosphorus content, a balanced C/N ratio, a high degree of humification and stability level, an acceptable porosity and bulk density. In addition, no pathogenic microorganisms were detected, indicating that the compost is safe. Also, the levels of thallium, cadmium, chromium and lead were below the standards.[54] composted POW with mowing wood and olive pruning wood and the final compost was evaluated for pH, electrical conductivity, elemental composition, dynamic respiration index, phytotoxicity, fluorescence and infrared spectroscopic fingerprints. The final results proved that the obtained compost has a good concentration of plant nutrients, no phytotoxicity and low heavy metal content, suggesting a safe use as an amendment in agriculture.[55,56] Aerobic-thermophilic composting was evaluated by Saidi et al.[57] as the most reasonable way to take advantage of the organic matter in the lignocellulosic biomass of POW, collected from the beaches of Tunisia, for agricultural purposes. Mininni et al.[58] prepared two composts named Cp20 and Cp60 from POW mixed with vine shoots and plant waste at rates between 20 and 60% on a fresh weight basis (Table 1). According to the results of their study, POW-based composts, especially Cp20, can be considered as valid alternatives/peat substitutes in growing media used for the production of melon and tomato plants. Since April 2009, the application of POW and other seaweed residues to produce composts is allowed in Italy up to 20% by fresh weight of the initial mixture.

Valorization of POW as a potential source of carbohydrate active enzymes

The POW biomass consists mainly of cellulose, hemicellulose and lignin.[59] The associated microbial community can fragment and break down these biopolymers especially polysaccharides by encoding Carbohydrate-Active Enzymes or CAZymes, which find various industrial and biotechnological applications such as bioconversion of POW biomass into sugars, fuels and other bioproducts of interest.[24,60,61] The metagenomic analysis performed by Rubio-Portillo et al.[24] permits to identify the microbial community associated with POW. Alphaproteobacteria, *Gammaproteobacteria, Bacteroidetes* and *Cyanobacteria* were the dominant members, while Pseudoalteromonas was the dominant genus, followed by *Alteromonas, Labrenzia* and *Aquimarina*. This study clearly shows that the POW constitutes a unique natural source of novel bacteria that produce CAZymes not detected in other environments, in particular, the proteins associated with cellulosome modules and the enzymes degrading cellulose, hemicellulose and lignin. These novel enzymes can be used in many applications, including cotton manufacturing and paper recycling industries, agricultural and food processing industries, as well as in bioenergy production from low-cost lignocellulosic biomass (Table 1).[24]

Valorization of POW as biomass source for bioenergy generation

Bioconversion of POW into biofuels has been considered in many countries in the Mediterranean area due to its availability and renewable nature.[1,54,55,62] Deniz et al.[63] conducted a survey on the application of hydrothermal gasification of POW in Turkey, while Balata and Tola[64] conducted a cost-opportunity analysis of the energetic bioconversion of POW in tourism-oriented Medeterran countries. Chiodo et al.[50] studied the application of pyrolysis of POW in relation to and compared it with other woody biomasses. POW was converted to bioethanol as part of a biorefinery strategy based on the use of lignocellulosic biomass, initially created with residues from wood product processing or agriculture.[62,65–67] Acid and enzymatic hydrolysis of POW were optimized and conversion yields to cellulosic bioethanol were studied and evaluated both in Erlenmeyer and in a 2-liter fermenter. The final bioethanol yields were around 62.3% with productivities of 0.46 and 0.76kg/m3 h in flasks and bioreactor, respectively (Table 1).[65]

Table 1 Recapitulation of potential applications of *Posidonia Oceanica* waste

Main finding	References
Valorization of pow as a source of natural bioactive compounds	
• *P. oceanica* residues as a source of promising anti-inflammatory, antioxidant, anti-diabetic and anti-glycation bioactive molecules. • Several studies demonstrated that *P. oceanica* residues extract showed antioxidant, antifungal and antiviral activities. • The high content of phenolic compounds (phenolic acids and flavonoids) in *Posidonia* extract are responsible of antioxidant and pharmalogical proprieties. • Resulting phenolic compounds can be utilized in cosmetic product formulation used for UV protection.	5,9,13,19,25,68
• Obtained extract fom *P.oceanica* reduce gene and protein expression of MMP-2 and MMP-9 gelatinases resulting in gelatinolytic activity inhibition and limitation of HT1080 cell migration and invasion. • These findings suggest that *P. oceanica* extract as source of interesting products, can be used for diseases prevention or treatment associated to an abnormal expression of MMP-2 and MMP-9 expression.	12, 17
• *P. oceanica* extract inhibit the migration human SH-SY5Y neuroblastoma cells by inducing cellular morphological and cell differentiation modification. These positive results are encouraging for further studies in neuroblastoma treatment. • Research finding indicate that *P. oceanica* extract provide an antitumor effect suggesting *P. oceanica* is a source of cancer cell migration inhibitor.	18
• Extract of *P. oceanica* leaves is able to regulate intestinal glucose transporters by reducing glucose uptake, specifically through a significant downregulation of the GLUT2 glucose transporter. • The results of the study imply that the phytocomplex of *P. oceanica* may have a protective effect against intestinal cell dysfunction, which contribute to the growth of inflammatory disorders linked to oxidative stress.	69
• High content of phydroxybenzoylation level in *P. oceanica* lignin supply a potential and environmentally acceptable source of p-hydroxybenzoic acid which employed for the production of chemicals (parabens) or pharmaceuticals (paracetamol). • Another study confirms the potentiality of *P. oceanica* phytocomplex in skin cell improvement, which could be useful in cosmetic industry.	16,70
• Associated strains with *P. oceanica* demonstrate the abilities to produce various bioactive compound like quorum sensing and quorum quenching molecules.	22,23,71
Valorization of pow as a source of preparation of fibers, cellulosic derivates and fiber-reinforced composite materials	
• *Posidonia oceanica* leaves were used to effectively produce cellulose nanocrystals. The results demonstrate an interesting structure and proprieties of obtained cellulose nanocrystals which have a significant potential in nanocomposites approach like reinforced polyester composites manufacturing.	38,45,72
• *P. oceanica* fibers accelerate the decomposition of the polymeric matrix specifically polyhydroxyalkanoates (PHAs), resulting in rapid and complete disintegration of film. • The technical feasibility of composite production using PHAs and P. *oceanica* fibers provide a solution to the problem of waste accumulation on beaches.	28
• *Posidonia* waste present a sustainable and promising source of cellulose nanocrystals with highest performance demonstrated remarkable sound absorption proprieties allow a wide range of fequency (100-1000 Hz) • With their improved proprieties, cellulose nanocrystals have enormous potential in the development of bio-based materials such us superior quality film, which are suitable for food packaging purposes as well.	15,46,73,74
• The incorporation of *P.oceanica* fiber into cement matrix enhance their thermal and mechanical proprieties. • The use of *P. oceanica fiber* as a good reinforcement in cement matrix and lime mater suggest a promising application in the construction industry. • *P. oceanica* fiber can be used as reinforcing agent in several material construction such us biodegradable thermoplastic matrix (Polyethylene Composites…), wood composite, wet-laid nonwoven production.	27,29,30,34,35,40,41,75,76
• Cellulose and its derivative were successfully produced from *Posidonia* waste. The resulting cellulose nanofibril (CNF) and carboxymethyl-cellulose *(CMC)* were characterized and showed an interest micro-nanomaterial.	37,39,77,78
• Valorization of *P. oceanica* fibers for the adsorption of heavy metals like orthophosphate, cadmium, copper, lead, uranium and chromium. • The activated seagrass exhibited 95 % of removal efficiency for methylene blue and Pb2+ from polluted brackish water. • *P. oceanica* residues exhibit a high removal efficiency of phosphate from a real waste water with adsorption capacity of 179.1 mg g−1.	36,43–44,45,79–81
• Use of *Posidonia* dead leave material as an adsorbent for removing dye such us Metal-complex dyes from industrial waste: • *Posidonia* fibers demonstrated their capacities to remove a direct dye Congo red with an efficiency of 80 %. • High yellow dye retention capability by *Posidonia* fibers.	31–33,36,82,83
• Dead leaves of *P. oceanica* reveals a maximum biosorption capacity of approximately 127 mg/g at initial phenol concentration of 500mg/L. • *P. oceanica* dead leaves can be used as a reliable, inexpensive biosorbent for the removal of phenol.	84
• *P. oceanica* biomaterial was applied as a bio-adsorbent of oxytetracycline, indicating the great capability for organic and me by in organic pollutant adsorption.	33,85

Table 1 Continued...

Main finding	References
Valorization of pow as a source of fiber and minerals in ruminant nutrition	
• Physicochemical characterisation of *P. oceanica* was performed in order to evaluate its nutritional composition. The result revealed that *P. oceanica* banquette rich in ash, fiber, minerals and poor in protein. These data show that *P. oceanica* banquette might be used as a feed source for ruminants.	8
• This study examined the effect of *Posidonia* supplementation on health and milk production, revealing an increase milk fat amount without having any deleterious effects on health and metabolic state of goats. • Therefore, using *Posidonia* waste as a substitute for straw, can be considered a viable source of forage for goats.	48
• This work evaluated the impact of substitution of barley straw by *Posidonia* at different fractions (15, 30 and 60 % of total forage) on sheep health and found that substituting 15 % of PO improve the nitrogen utilization by sheep without negative effect, by contrast substitution of 60% affect metabolism state. • According to this study *P. oceanica* banquettes can be used a source for forage in sheep feeding but with a quantity well defined does not exceed 30% of total forage.	49
Valorization of pow for the thermochemical production of biochar	
• Theses studies investigate the generation of Biochar from *Posidonia oceanica* using thermochemical processes such pyrolysis and cabonization. The maximum yield of resulting biochar was around 27%. • *P. oceanica* biochar exhibit an interesting characteristic compared to those obtained from wood suggesting their implication in various application like heavy metal removal from waste water	50–52
• *P. oceanica* as an original marine biomass holds a promising and sustainable source for enhanced quality of biochar • Owing to their higher stability biochar utilization, as a soil mediator, improve the plant growth by ameliorating soil proprieties, showing their use as a suitable land fertilizer.	53,86
Valorization of pow for the production of compost	
• *Posidonia* waste combined with sediment-based composts is used as a constituent in techno-soils and in nursery growth substrate, making co-composting an effective alternative for decontaminated sediments and *P. oceanica* residues valorization.	56
• According to this study, using *P. oceanica* fibers o compost as plant substrates enhances lentil seeds germination like melon and tomato plants, indicating that *Posidonia* waste holds great potential for agricultural purposes.	58,87
• This study shows that utilizing of *Posidonia*-based compost as a component in soil substate promotes the growth of ornamental plants *(Viburnum tinus. L)*. These findings encourage the use of *Posidonia* waste as a promising substrate for food production.	88
Valorization of pow as a potential source of carbohydrate active enzymes	
• The current study shows that using *P. oceanica* cellulose as supplemented in medium, promote bacterial growth and cellulase production. This indicates the potential of valorizing *Posidonia oceanica* cellulose as a novel inducer substrate for the production of a pool of three cellulases like CMCase, FPase and β-glucosidase by S. roseochromogenes. • *S. roseochromogenes* as a potential new cell factory for enhanced cellulase production, could be utilizing for bioconversion of cellulosic wastes into bioethanol.	59
• Associated microbiome with *P. oceanica* waste was characterized, showing a domination of bacteria producing CAZymes. These results confirm the potential of *P. oceanica* waste is a source of diverse bioactive compounds and CAZymes.	24
Valorization of pow as biomass source for bioenergy generation	
• *P. oceanica* as a potential source of bio-based activated carbons. • Obtained activated carbons from P. *oceanica* waste was applied to develop an eco-friendly lithium-sulfur battery with high capacity	86,89
• Obtained oil yield from P. oceanica biomass ranged from 41.4 to 47.2% which was similar to that obtained from woody biomass. Moreover, bio-oil derived from *P. oceanica* have interesting	50
• Production of syngas, bio-oil, and biochar by pyrolysis from *Posidonia oceanica* residues with improved yield. • *Posidonia oceanica* residues can be utilized for bioenergy production through acidic thermal hydrolysis followed by anaerobic digestion process. biogas production reaching up 0.241 ± 0.065 Nm3 per kgVS of wet Posidonia present an interesting finding, that might make it a viable example of the circular economy idea.	67,90
• This study investigated the capability of *P. oceanica* residues as a biofuel with maximum ethanol yield of 62.3% and a productivity 0.76 kg/m^3 h in 2 L bioreactor after 12h of fermentation. • The outcomes demonstrated the potential of P. oceanica biomass as a promising feedstock for bioethanol production.	65

Conclusion

POW represents an environmental, economic, social and hygienic problem in the tourist areas of the Mediterranean basin. However, its richness in high added value compounds opens the way to its application in food, cosmetic, pharmaceutical and energetic fields, offering a double advantage of valorization and environmental management. Different green and eco-compatible technologies have been recently developed for the extraction of fibers, polyphenols and bioactive molecules from POW, useful in different industrial and biotechnological applications. The bioconversion of POW into biofuels seems to be the most promising valorization strategy, but its application remains confined to laboratories. Further efforts are needed to improve and scale up the conversion process to an industrial scale.

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Authors' contribution

M Neifar and A Cherif conceived the study, A Souii prepared the manuscript draft. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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