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Review

Biochar: Production, Applications, and Market Prospects in Portugal

Bruno Garcia [1], Octávio Alves [1], Bruna Rijo [1], Gonçalo Lourinho [1] and Catarina Nobre [2,*]

[1] CoLAB BIOREF—Collaborative Laboratory for Biorefineries, 4466-901 São Mamede de Infesta, Portugal; bruno-garcia@bioref-colab.pt (B.G.); octavio-alves@bioref-colab.pt (O.A.); bruna-rijo@bioref-colab.pt (B.R.); goncalo-lourinho@bioref-colab.pt (G.L.)

[2] VALORIZA—Research Centre for Endogenous Resource Valorization, Polytechnic Institute of Portalegre, 7300-555 Portalegre, Portugal

* Correspondence: catarina.nobre@ipportalegre.pt

Abstract: Biochar produced during the thermochemical decomposition of biomass is an environmentally friendly replacement for different carbon materials and can be used for carbon sequestration to mitigate climate change. In this paper, current biochar production processes and top market applications are reviewed, as well as emerging biochar uses gaining momentum in the market. Various application fields of biochar, including agricultural applications (e.g., soil conditioning), adsorption (for soil and water pollutants), carbon sequestration, catalysis, or incorporation into composites or construction materials, are also presented and discussed. According to this literature overview, slow pyrolysis is the preferred process for biochar production, whereas agricultural applications (for soil conditioning and fertilization) are the most studied and market-ready solutions for biochar use. The Alentejo region (Portugal) shows tremendous potential to be a major player in the developing biochar market considering feedstock availability and large areas for biochar agricultural application. Biochar's production potential and possible benefits were also estimated for this Portuguese region, proving that agricultural application can effectively lead to many environmental, economic, and social gains.

Keywords: biochar; applications; pyrolysis; EU legislation; markets; SWOT analysis

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1. Introduction

Biochar is a carbon-rich amorphous and aromatic material that may present various interesting properties such as high hydrophobicity, alkaline nature, relevant concentrations of nutrients (N, P, and K), good water and nutrient retention capacities, low thermal conductivity, high energy content, and high superficial porosity that enable interaction with external organic and inorganic compounds [1–3]. These properties are largely dependent on feedstock type and biochar production conditions. Although biochar is mostly recognized as a valuable resource for soil fertilization and conditioning, this material also has significant potential to be used for water filtration and remediation processes, as an animal feed supplement, for greenhouse gas (GHG) emission control (carbon sink feature), for insulation materials for the building sector, as an electrode material (for energy production and storage), cosmetic products, biogas production and improvement, and in catalytic processes. The costs involved in its production and the unsuitability of some samples for soil incorporation have encouraged the use of biochar in domains other than agricultural activities and the investigation of new alternatives with more favorable economic returns [2–4].

Although biochar shows widespread application prospects in terms of mitigating environmental issues, the actual impact of biochar on the environment is still unclear, in particular the possible release of polycyclic aromatic hydrocarbons (PAH) and metal ions, which needs to be further investigated during its application [5]. Moreover, legislation regarding biochar is still under development, and existing policies are mostly related to its widespread use in the agricultural sector, particularly as a fertilizing product [6].

In order to fully harness biochar's promising properties, research and development on different carbonization technologies are still required, particularly to improve process efficiency and environmental sustainability (e.g., energy integration, proper use of byproducts in a circular perspective), and ensure that biochar has enough quality for the intended end-use. As such, standardized systems for biochar production and use (which currently are mostly voluntary certification schemes) need to be further established to allow biochar markets to develop in the coming years [5,7].

This paper intends to briefly describe current biochar production technologies as well as biochar's top market and emergent applications. An overview of biochar's European legislative framework is also performed, which is of relevance not only to assessing biochar's legal definition and quality parameters but also to assessing current and future market prospects.

2. Biochar Production Technologies

Amongst the well-known carbonization processes, pyrolysis, gasification, hydrothermal carbonization (HTC), and torrefaction are generally employed to obtain biochar from several raw materials and for various types of applications.

Slow pyrolysis is a thermal conversion technology conducted at temperatures between 300–800 °C, aiming to maximize biochar yield. The process is performed at atmospheric pressure, and it is characterized by a relatively long residence time and low heating rates [8]. Different types of reactors have been used for biochar production via slow pyrolysis, such as agitated drum sand rotating kilns, wagon reactors, and paddle pyrolysis kilns. Moreover, in this process, high biochar yields are favored when using feedstocks with high lignin and ash content, along with large particle sizes. These characteristics improve biochar yield by increasing cracking reactions that reduce the amount of bio-oil (liquid products). On the other hand, fast pyrolysis offers particularly promising advantages in maximizing bio-oil yield (up to 75 wt.%), basically due to the very significant heating rates (over 200 °C/min) and shorter residence times [9].

Unlike pyrolysis, the gasification process is carried out in the presence of an oxidizing agent, and it is primarily used for syngas production (i.e., H_2, CO, CO_2, CH_4). As a result, biochar is considered a byproduct, and yields are low (<25%), resulting in limited research on the feasibility of biochar production [3,10].

Besides pyrolysis and gasification, torrefaction is an emerging approach for biochar production. In this process, moisture, CO_2, and O_2 contained in biomass are removed under inert conditions at 200–300 °C and long polysaccharide chains are depolymerized to produce a hydrophobic solid product with a low O/C ratio [11]. This process is generally operated with a slow heating rate; hence, it is also known as mild pyrolysis. Nonetheless, torrefaction is not considered a promising technique for biochar production, regardless of the higher product yields (70–80 wt.%), because torrefied biomass still contains a significant fraction of volatile components from raw biomass and the physical-chemical properties do not meet biochar requirements (e.g., O/C > 0.4). As a result, torrefaction is often used as a biomass pre-treatment process for moisture removal, feedstock densification, and increased brittleness [12].

Opposite to pyrolysis and torrefaction, which are carried out under a dry atmosphere, HTC proceeds in wet conditions and can also be referred to as wet pyrolysis or wet torrefaction. This process is performed in a biomass-water solution at temperatures of 180–300 °C and autogenous pressure (subcritical conditions) for several hours. Similar to pyrolysis, HTC presents significant biochar yields (50–80 wt.%), but also a liquid fraction composed of a bio-oil and water mixture (5–20 wt.%), and a gas phase that mainly includes CO_2 (2–5 wt.%) [13]. The great interest in HTC for biochar production is that the process can avoid the energy-intensive drying step that is usually required for conventional pyrolysis, and thus minimize operational costs. Also, HTC can convert feedstocks having >75 wt.%

moisture content (diversifying feedstock options for biochar production) and decrease the leaching of salts and minerals, yielding biochars (or hydrochars) with reduced ash content [14].

Overall, slow pyrolysis is the preferred process for biochar production. The technology can be applied to almost all types of biomass feedstocks and the slow heating rates, coupled with low temperatures and long residence times, are appropriate for the formation of stable carbonaceous solid materials [15]. Moreover, it should be highlighted that for the above-mentioned processes, particularly pyrolysis, torrefaction, and HTC, there are other products of interest, such as bio-oil, which can be further processed into drop-in liquid biofuels; wood vinegar, which can be applied as a biopesticide; or HTC process water, which shows potential to be used in hydrothermal gasification for producing renewable gases or synthetic liquid biofuels. Addressing the application of these by-products is of extreme relevance to achieving circularity and, consequently, increased sustainability in biochar production.

Table 1 summarizes and compares the typical operating conditions and biochar yields of the described biochar production processes.

Table 1. Comparison of thermochemical processes for biochar production [9,12,13,15–17].

Process	Temperature (°C)	Residence Time (min)	Pressure (atm)	Other Conditions	Biochar Yield (%)
Slow pyrolysis	300–800	>60	1	No oxygen; Moisture content < 15–20%; Heating rate < 10 °C/min	30–55
Fast pyrolysis	450–600	~0.02	1	No oxygen; Moisture content < 15–20%; Heating rate ≥ 200 °C/min	10–25
Gasification	750–1000	0.2–0.4	1–3	Limited oxygen supply Moisture content 10–20%; Heating rate ~1000 °C/min	14–25
Torrefaction	200–300	15–60	1	No oxygen; Moisture content < 10%; Heating rate < 50 °C/min	70–80
HTC	180–300	5–240	1–200	Moisture content 75–90%	50–80

In line with the chosen production process, the physical-chemical properties of biochar are very important to define its final application. Biochar characteristics and yields are highly dependent on feedstock and operation parameters, particularly temperature. Ippolito et al. (2020) studied the influence of feedstock choice and process parameters on main biochar properties through a meta-analysis. The authors assessed that process type plays a minor role in biochar's physical-chemical properties, whereas temperature is the dominating parameter. Higher process temperatures can be responsible for increased carbon content and specific surface area (SSA) properties that promote soil improvement when using biochar. The authors also stated that feedstock choice has the largest influence on biochar properties, with wood-based feedstocks presenting higher SSA and crop- and grass-based biochars showing increased cation exchange capacities (CEC). The overall results of the study, including temperature and feedstock variations, are represented in Table 2 [18].

Table 2. Basic biochar physicochemical and morphological properties (expressed on a dry basis) [18].

Property	SSA (m^2g^{-1})	CEC (cmol kg^{-1})	AEC (cmol kg^{-1})	CCE (%)	PV (m^3 t^{-1})	APS (nm)	Ash (%)	pH	EC (dS m^{-1})
Pyrolysis type									
Slow	183	44.9	4.90	6.10	2.04	52.3	19.2	8.7	4.45
Fast	98.6	48.1	5.33	11.2	3.66	1190	22.0	8.7	5.85

Table 2. *Cont.*

Property	SSA (m^2g^{-1})	CEC (cmol kg^{-1})	AEC (cmol kg^{-1})	CCE (%)	PV (m^3 t^{-1})	APS (nm)	Ash (%)	pH	EC (dS m^{-1})
Feedstock									
Wood-based	184	23.9	5.65	9.04	7.01	74.6	10.2	8.3	6.20
Crop wastes	98.2	56.3	4.51	6.12	2.05	2320	21.1	8.9	5.72
Other grasses	63.4	63.3	5.05	n.d.	3.36	268	18.0	8.9	5.20
Manures/biosolids	52.2	66.1	7.77	14.2	0.82	27.3	44.6	8.9	3.98
Process temperature (°C)									
<300	27.1	44.4	n.d.	7.16	0.06	8.16	12.3	6.0	3.60
300–399	57.2	52.8	3.65	9.17	3.45	2340	17.8	7.8	5.72
400–499	108	35.0	n.d.	9.08	1.18	78.0	19.0	8.5	2.77
500–599	97.2	56.4	3.38	10.1	4.68	1140	23.2	9.0	8.05
600–699	178	33.7	n.d.	9.50	1.77	2000	23.5	9.5	4.85
700–799	204	53.0	5.27	12.9	8.87	9.19	26.6	10.0	4.29
>800	208	85.3	8.83	19.6	0.09	8.45	28.5	9.9	6.44

Note: Biochar properties considered for pyrolysis type and process temperature correspond to average values of all biochars analyzed in the study. SSA—Specific Surface Area; CEC—Cation Exchange Capacity; AEC—Anion Exchange Capacity; CCE—Calcium Carbonate Equivalent; PV—Pore Volume; APS—Average particle Size; EC—Electrical Conductivity.

As seen in Table 2, different feedstocks show different properties that affect biochar mass and energy yields and their designated applications [8,19]. Feedstocks rich in nutrients, such as manures and biosolids, produce biochar with high nutrient content, which is reflected in their values of CEC, AEC, CCE, and ash content. Moreover, wood-based biochar presents increased values of SSA and PV, meaning that these biochars have very significant potential for the removal of organic pollutants, carbon sequestration, and amending soil pH [20]. The pore size may vary between 2–18 nm (mesopore range) when the biochar is obtained from the pyrolysis of rice straw and tends to decrease with the process temperature [21]. Regarding biochar yields and feedstock variability and composition, in general, higher biochar yields can be obtained from feedstocks with higher ash contents, but the effect is less pronounced for ash contents >5% [22]. According to different studies, cellulose and hemicelluloses are the most promising components in producing volatile products via thermochemical conversion (e.g., pyrolysis) because these two compounds have a lower molecular weight than lignin and are easily released as pyrolytic gas. On the other hand, lignin is the main component responsible for biochar production due to its resistance to thermal degradation; as such, feedstocks with higher lignin contents generally lead to higher biochar yields [19,20].

Temperature is considered the most important parameter in controlling carbonization reaction mechanisms. This property influences the characteristics and yield of biochar to a greater extent when compared with residence time, heating rate, or feedstock particle size [8]. In general, process temperature affects SSA, pH, carbon content, stability, volatile fraction, and other biochar physical-chemical properties. Biochar produced at low temperatures can present high acidity, polarity, and low aromatic content, as well as low hydrophobicity. When process temperature is increased, acid functional groups (e.g., hydroxyl or carboxyl) and mass yields are reduced, meaning that alkaline functional groups increase along with pH and ash content. In addition, as a consequence of higher process temperature, volatile compounds are further released, resulting in larger SSA values and a more developed pore structure (increased PV) [9]. These features of high-temperature biochars indicate that their most suitable applications are related to the sorption or retention of nutrients and contaminants (organic and inorganic), while PV is assumed to affect water availability and soil aeration. Some authors have been emphasizing that biochar particle size can affect plant nutrient content, nutrient availability in growing media or soils, and

PAH content [23–25]. The addition of biochar particles of different sizes can directly affect biochar-soil interactions, causing changes in the soil's physical properties. The smaller the biochar particles, the better the mixing and interaction with soil particles [26]. Given that biochar's characteristics are influenced by several parameters, the corresponding biochar properties also vary widely. This fact relates to arguably the most prominent aspect of biochar as a marketable product: the ability to be "tailor-made". Since biochar is becoming increasingly used in several areas, standardization before its final use is extremely important to generalize and predict its performance in different applications.

3. Biochar Applications

In the following subchapters, a description of potential biochar applications and related studies is presented to provide an idea regarding market diversity for these materials.

3.1. Agricultural Applications

Several studies have reported that the use of biochar for soil amendment improves soil physical properties, hydrological characteristics, water content, and water use efficiency, as well as soil fertility and crop yields [27]. Mixing biochar with decomposed manures, composts, and crop residues also improves nutrient use efficiency.

Soil application methods are heavily influenced by farming system type, labor availability, and power machinery available [28]. In Portugal, soils have very little carbon content. Thus, "tailor-made" biochars can be developed for particular soils and crops to achieve specific outcomes [29]. Despite these benefits, the feasibility of using biomass wastes to produce biochar for subsequent use in agriculture depends on its environmental and economic performance. Limitations exist since farmers are often risk-averse and have less investment capacity than other potential users, and there is still an enormous variability in the predictability of biochar impacts [30,31]. Agricultural biochar markets are also very seasonal, requiring producers to store large quantities of biochar or find alternative markets. The European biochar market has been mostly focused on livestock, with 90% of the biochar produced being used in livestock farming, whether mixed with feed, added to litter, or used in the treatment of slurries. This situation may be mainly due to the lack of regulation regarding the application of biochar as a soil amendment [32]. Therefore, in terms of marketability, it is important to understand which benefits matter the most to each farmer and which specific product biochar can potentially replace. Furthermore, the cost of biochar is critical for determining livestock pricing [33]. Some published cases of biochar use in agriculture are summarized in Table 3.

Table 3. Summary of studies about biochar applications in agriculture and livestock farming.

Biochar Use	Application Conditions	Obtained Results	References
Soil amendment	Grapevine pruning biochar was applied to vineyard clay soils	■ Available water content increased by 23%	Marshall et al. (2019) [34]
	Biochar was applied to sandy loam soils at 5% (w/w) and 12.6 dS m^{-1} salinity rate	■ Sorghum dry matter yield increased by 27.71% ■ Biochar alleviated the harmful impact of salinity	Ibrahim et al. (2020) [35]
	Eucalyptus wood waste biochar (550 °C) applied to different soils of mixture grassland (10 t ha^{-1})	■ Improved legume production and competitiveness over grasses in mixed pastures ■ Increase in the amount of N fixed	Mia et al. (2018) [36]
	The addition of biochar to soils promoted an increase in crop yields	■ Liming effect ■ Improved water holding capacity of the soil ■ Improved nutrient availability of crops ■ Around 77% of the studies found that < 50% (by vol.) of biochar addition in container substrates promoted plant growth, in particular, herbaceous plants	Jeffery et al. (2011) [37] Huang and Gu (2019) [38]

Table 3. *Cont.*

Biochar Use	Application Conditions	Obtained Results	References
Composting additive	Biochar was applied at a 10% rate (wt.%)	■ Biochar at 10–30% rates succeeded in mitigating NH_3, N_2O, and CH_4 emissions ■ Biochar decreased the bioavailability of Cu and Zn in compost	Sanchez-Monedero et al. (2017) [39]
	Woody biochar (550 °C) was applied at a 10% rate (wt.%) to a mixture of slaughter waste, swine slurry, and sawdust compost	■ Reduction of ammonia volatilization by 26–59% ■ Increase in nitrate (NO^{-3}) accumulation by 6.7–7.9 fold ■ Enhanced macro- and micro-nutrient content	Febrisiantosa et al. (2018) [40]
Peat substitute & Growing medium	Biochar as a peat substitute	■ Biochar can replace peat (≤ 70 vol.%) in soil-free substrates (no pH adjustment) without negative impacts on marigold biomass or flowering. ■ Incorporation of 50% (by vol.) biochar with peat increased container capacity, due to increased micropores, compared to those with 100% peat substrate. ■ Incorporation of 20% or 35% (*w*/*w*) biochar with compost made from green waste increased container capacity. ■ Incorporation of 60% and 70%, by vol. of the mixed hardwood biochar could substitute peat-based substrate in containers to grow plants.	A.J. Margenot (2018) [41] Méndez et al. (2015) [42] Zhang et al. (2014) [43] Huang et al. (2019) [44]
	Mixtures of Biochar (at 0, 20, and 35%), humic acid (at 0, 0.5, and 0.7%), and composted green waste	■ The highest quality medium and best growth were achieved with 20% biochar and 0.7% humic acid. ■ Improved the particle-size distribution. ■ Adjusted the bulk density (BD), porosity, and water-holding capacity (WHC) into ideal ranges. ■ Decreased pH and electrical conductivity (EC). ■ Increased macro- and micro-nutrient contents and microbial biomass C and N of the growth media.	Zhang et al. (2014) [43]
	Rice husk biochar mixed with perlite (1:1) as hydroponics growing medium	■ 2 fold increase in shoot length, number of leaves, and fresh/dry masses of leafy vegetable plants ■ Increase of 1.2 to 3.5 fold in leaf K, Mg, Mn, and Zn contents in most vegetable plants ■ Decreased algal growth in the nutrient solution	Awad et al. (2017) [45]
Bedding litter	Addition of biochar at 10 to 20 wt.% to pine shavings for poultry bedding	■ Increased water holding capacity by 21.6 and 32.2%	Linhoss et al. (2019) [46]
Feed Additive	<1% of daily rice husk biochar diet to ruminants, goats, and pigs; 2–6% of daily woody biochar feed to ducks and poultry	■ Increased weight gain, digestibility, N retention; increased egg weight ■ Lowered feed conversion ratio and enteric CH_4 emissions; decreased pathogens	Man et al. (2021) [32]
Heavy metal immobilization	Biochar was applied (up to 10% rate) to heavy metal-contaminated soils.	■ Effective heavy metal (Cd, Pb, and Zn) immobilization ■ Decreased metal uptake in lettuce	Kim et al. (2015) [47]
Soil reclamation	Wheat straw biochar and NPK added for sandy soil reclamation	■ Improved soil physical and chemical properties. ■ Increased total organic carbon content ■ Increased volumetric water content ■ Increased sandy substrate fertility ■ Achieved conditions for revegetation	Bednick et al. (2020) [48]

3.2. Control of GHG Emissions

Currently, 60% of the global warming effect is caused by CO_2 emissions, meaning that new strategies must be implemented to control carbon dioxide levels in the atmosphere. Biochar has an interesting ability to retain significant amounts of carbon for longer periods that may range from decades to thousands of years. In particular, biochar can be used for carbon sequestration by retaining CO_2 captured by the vegetable feedstock used for its production. When applied as a soil amendment, biochar contributes to climate change mitigation by fixing carbon in stable aromatic bonds that are resistant to microbial degradation. This stability reduces immediate labile carbon release into the atmosphere. Moreover, other GHG emissions such as N_2O and CH_4 are significantly minimized, depending on soil type, with reductions that may achieve more than 50%, considering the introduction of biochar amounts equivalent to 10% of soil mass and 20 t ha^{-1}. Conversion of animal or vegetable feedstocks into biochars also minimizes GHG emissions through the natural decomposition of such feedstocks [3,4,49].

A different carbon sequestration method involves the use of biochars to adsorb the CO_2 contained in industrial flue gases as a replacement for other high-cost materials (e.g., zeolites, porous polymers, and metal oxides). This process takes advantage of the good properties of biochar in terms of porosity and surface area (0.4–0.9 $cm^3\ g^{-1}$ and 1000–2000 $m^2\ g^{-1}$, respectively), but requires a chemical activation post-treatment using KOH or sodium amide. Activated biochars produced from biomass feedstocks like hazelnuts, garlic peels, and olive oil wastes have shown adequate properties to adsorb CO_2, with retention efficiencies between 3.5–6.2 mmol g^{-1}. As an alternative, flue gases may be conducted through a bed of biochar heated at high temperatures and in the absence of oxygen to convert CO_2 into CO that may be employed for subsequent energy applications [3,50]. Table 4 presents studies focused on possible biochar uses for GHG mitigation.

Table 4. Summary of studies about biochar applications for GHG emissions abatement.

Biochar Use	Application Conditions	Relevant Results	Reference
CO_2-capture	▪ Biochar was obtained from pyrolysis of olive stones and almond shells, followed by CO_2 activation. ▪ The capture experiment consisted of the gas passage (with N_2 + CO_2) through a fixed-bed adsorption unit with biochar (25 °C and 100 °C, 1 atm).	CO_2 adsorption performance was better for biochar from olive stones at 25 °C (3 mmol g^{-1}). Good regeneration capabilities were found for both biochars.	González et al. (2013) [51]
CO_2-capture	▪ Biochar was prepared from hydrothermal carbonization of *Jujun* grass and *Camellia japonica*, and KOH/N_2 activation. ▪ Tests were conducted in a gravimetric analyser (25 °C, 0.15–20 bar).	Adsorption results were similar for both feedstocks and ranged between 3–21 mmol g^{-1}, with the highest results achieved when the pressure increased.	Coromina et al. (2015) [52]
GHG mitigation	▪ Biochar preparation: pyrolysis of hardwood trees. ▪ Introduction of 49 t ha^{-1} of biochar for cultivation tests using *Miscanthus* crops, for 2 years.	Soils amended with biochar presented a reduction of CO_2 emissions of 33% and a global reduction of GHGs (CO_2, N_2O, and CH_4) of 37%.	Case et al. (2014) [53]
	▪ Biochar preparation: gasification of hardwood and softwood chips. ▪ Biochar was applied at a rate of 9.3 t ha^{-1} in field tests for the cultivation of corn and different types of grasses, during 148 days.	No significant variations in CO_2 emissions were observed for all crop types, but N_2O emissions were suppressed by 27% with corn crops.	Fidel et al. (2019) [54]

Although the use of biochar has demonstrated promising results for CO_2 capture contained in flue gases and GHG mitigation when applied to agricultural soils, results are strongly dependent on operational or application conditions. According to these studies, parameters like temperature and pressure significantly influenced CO_2-capture processes, while crop type and cultivation period affected GHG production during crop cultivation. Therefore, optimal conditions must be defined through field tests before establishing the best biochar for market purposes and intended applications.

3.3. Wastewater Treatment

Biochars can be considered a new low-cost alternative to commercial activated carbon applied in water disinfection and wastewater remediation processes. Batch adsorption studies have shown that biochars have significant adsorption capacities for contaminants present in real wastewaters, which is justified by their macroporous surface structure. These materials are therefore capable of remediating complex wastewaters while avoiding premature pore-clogging. The lower cost and history of land application combined with the need to remove new pollutants (e.g., antibiotics) has led to an increased interest in exploring biochars for new remediation solutions [55].

Conventional remediation strategies include, for instance, reverse osmosis, chemical oxidation or reduction, and precipitation. The use of biochars to adsorb aqueous contaminants presents important advantages over the aforementioned treatments, namely lower costs and the minimization of secondary by-products (e.g., sludges) [3]. Furthermore, biochar's surface characteristics may be enhanced through activation methods to reach a higher degree of porosity and density of functional groups, enabling their application in the removal of aqueous organic and inorganic pollutants. These activation processes can be categorized into physical or chemical activation, including ball milling, acid-base modification, clay mineral modification, or metal oxide modification [56]. Activation treatments can further develop biochar's pore structure and allow the development of functional groups (e.g., -COOH, -OH, and -CHO) that promote the capture of cationic and anionic inorganic contaminants, as well as organic pollutants (e.g., phenolic compounds and pesticides). Table 5 shows studies focused on biochar applications for wastewater treatment and general pollutant removal.

Table 5. List of studies focused on biochar applications for wastewater treatment.

Biochar Use	Application Conditions	Obtained Results	References
Wastewater treatment	Catalytic ozonation of refinery wastewater with activated biochar from petroleum waste sludge.	Removal efficiencies for the following contaminants: total organic carbon (53.5%), Ox (33.4%), NOx (58.2%), and OxS contaminants (12.5%).	Chen et al. (2019) [57]
Removal of heavy metals	Pb^{2+} removal from battery manufacturing wastewater using bagasse biochar.	Maximum removal efficiency of 12.7 mg g^{-1} (75.4%) of Pb^{2+} was reached.	Poonam and Kumar (2018) [58]
	Jazaurin, ficus, orange, and mango biochars were used as filter media to retain several heavy metals.	Biochars were more effective with particle sizes <0.1 cm and initial concentrations between 50–150 mg L^{-1}, generating 99% of removal efficiencies for Cu^{2+}, Cd^{2+}, Pb^{2+}, and Zn^{2+}.	Hefny et al. (2020) [59]
Removal of nitrogen and phosphorus	Dairy manure runoff batch sorption using biochars produced from biomass	Adsorption results of 20–43% of ammonium and 19–65% of phosphate were achieved within 24 h	Ghezzehei et al. (2014) [60]
	Phosphorous removal from treated municipal wastewater	Phosphorous was removed effectively with relatively fast kinetics (<8 h) and a good adsorption capacity (8.34 g kg^{-1})	Zheng et al. (2019) [61]
Removal of organic contaminants	Biochar was produced by thermal activation (600 °C) from anaerobically digested bagasse	Sulfamethoxazole and sulfapyridin were removed from aqueous solutions with maximum adsorption capacities of 54.38 mg g^{-1} and 8.60 mg g^{-1}, respectively	Yao et al. (2018) [62]
	Gliricidia sepium biochar was used in batch sorption studies to remove aqueous dyes	Biochars produced at higher temperatures presented better adsorption efficiencies	Wathukarage et al. (2017) [63]
Stormwater management	Use of sand and biochar filters	▪ Primarily removal of metals/metalloids and total suspended solids ▪ Minimal land requirement ▪ Limited nutrient removal ▪ High operation costs to prevent clogging	Mohanty et al. (2018) [64]
	Use of biochar in enhanced bio infiltration/bioretention system	▪ Removal of a wide variety of pollutants ▪ Demand for larger areas ▪ High installation and maintenance costs	
Constructed wetlands	Biochar was prepared from cattail and introduced into constructed wetlands	Results showed an improvement in removal efficiencies of chemical oxygen demand, NH_4^+ and total nitrogen, and a reduction of N_2O emissions. Heavy metals such as As^{2+}, Zn^{2+}, and Cu^{2+} were retained with rates of 35.4–83.9%, 8.2–23.7%, and 0.3–0.9%, respectively	Guo et al. (2020) [65]
	Biochar derived from wood was placed in a horizontal subsurface flow constructed wetland	Nutrient uptake by plant roots, plant biomass growth, and nutrient removal from wastewater were all enhanced with the biochar system. A pH reduction induced by plants in filter media was observed	Kasak et al. (2018) [66]

This literature survey demonstrated the large spectrum of contaminants that may be removed with biochars, as well as the diversity of effluents that may be remediated considering different adsorption techniques. In fact, the adsorption performances obtained in most studies were considered sufficiently good even without any biochar activation of physical or chemical nature, which represents a significant advantage in terms of lower energy demands, investment, and by-product generation during biochar preparation. Other benefits include plant biomass development when biochars are applied in constructed wetlands while performing wastewater remediation. These applications suggest that environmental remediation may be a promising strategy for biochar valorization in the near future with the emergence of new pollutants generated by households, rural activities, and industry.

3.4. Other Emerging Applications

Due to their inherent and versatile characteristics, biochars can also be used for alternative applications other than energy, agriculture, and wastewater treatment. The use of carbonaceous materials, for example, is one of the most well-established practices in material science. Over the years, the utilization of high-cost carbon materials in the field has struggled to reach beyond niche applications, despite their promising expectations in terms of final applications. Thus, research and development of innovative applications for biochars to replace carbon materials derived from non-renewable sources is a field that is becoming increasingly popular [67]. A brief summary of the recent literature regarding novel biochar applications is presented in Table 6.

Regarding the possible alternative uses for biochar mentioned in the previous table, applications in civil engineering and construction have already reached large-scale demonstrations or even limited commercial success. Therefore, there is enormous potential in the coming years for the development of novel products viable for commercialization. Other biochar uses in paper manufacturing or synthesis of composite materials are still at an early stage of development but also present promising results that can open a completely new approach for multiple markets.

Table 6. List of studies focused on emerging biochar applications.

Biochar Use	Application Conditions	Obtained Results	References
Biochar paper and cardboard	Biochar (up to 30%) and paper pulp were blended	▪ Extended shelf life ▪ Anti-static agent ▪ Promotes moisture absorption	Draper and Schmidt (2014) [68]
Biochar ink	Biochar was used as a substitute for carbon black in ink production	Similar visual density results were obtained as the standard carbon black ink	Hulse (2019) [69]
	Production of a biochar-based conductive ink	The product is compatible with printed electronics	Edberg et al. (2020) [70]
Biochar as construction material	Biochar was added to pavement bitumen (5–15%)	This application resulted in improved moisture and cracking resistance, as well as in an increased viscosity of the product	Gupta and Kua (2017) [71]
	Biochar applied at 5% cement replacement in mortar	▪ Compressive strength is slightly higher ▪ Water absorbed contributes to internal curing in mortar	
	A composite of biochar–clay plaster (30–50 wt.%) was mixed with clay and sand	▪ Promotes humidity control (45–70%) ▪ Retains toxic gases through absorption/adsorption ▪ Has low thermal conductivity	
Biochar composites	Biochar (10 wt.%) was added as a filler to glass fibre reinforced composite	Compared to glass fiber reinforced polymer, the new composite material presented: ▪ greater damping impact properties ▪ a storage modulus that was 28% higher ▪ a better thermal stability ▪ better flame retardancy properties	Dahal et al. (2019) [72]

4. Policy & Legislative Framework

Biochar applications (described throughout Section 3) are relatively new, justifying the existing gap in national and EU legislation regarding biochar production and use. Nowadays, the use of biochar as a fertilizing agent is regulated on a national level in some European Union Member-States (EU-MS). Most EU countries do not have specific regulations for biochar, although all countries have regulatory procedures to use these materials for soil fertilization, meaning that one can apply for registration to use biochar as a fertilizer product. Different definitions and regulatory procedures regarding fertilizing products and corresponding requirements exist in the EU-MS. Furthermore, there is still no specific EU regulation for biochar. Table 7 summarizes the state of biochar regulation in the EU [73,74].

Table 7. Current regulations on biochar [75].

European Regulation	National Regulation		Voluntary Regulation
Not in force yet. Proposals are being developed and are expected to be implemented soon. It is anticipated that carbon and nutrient-rich biochars will be regulated by "end-of-waste criteria".	In force in Germany, Austria, Switzerland, and Italy. Biochar of vegetable origin only.	In other EU countries, free trade is only possible after obtaining registration or a permit.	Serves certification but does not have a legal basis. There are three main organizations: European Biochar Certificate (EBC); Biochar Quality Mandate (BQM); and International Biochar Initiative (IBI-BS).

However, a new regulation on a range of fertilizing products (revision of EC Regulation 2003/2003) has been launched in 2016 by the European Commission (EC) as part of a package to stimulate the circular economy within the EU27. The proposal has been amended by the European Parliament (EP) and by the Council. In October of the same year, the EP agreed to a series of amendments (282), and in December 2017, the Council agreed with a proposal. Due to this new legislative framework, biochar is expected to be included in the REACH regulation (EC Regulation 1907/2006). This regulation is a system set up for the Registration, Evaluation, Authorization, and Restriction of Chemicals. A REACH registration is required if a fertilizing product is sold in quantities of one tonne or more per year [75,76].

Furthermore, the EC also proposed that wastes that meet the requirements of the new regulation on fertilizing products will get an "end-of-waste" status, which means that the regulatory requirements for waste do not apply. This classification may solve the question of whether biochar is a waste, a by-product, or has another status, providing a definite legal definition for biochar. As such, the EC has entrusted the Joint Research Centre (JRC) to propose "end-of-waste" criteria for biochar (and for struvite and incineration ash), through a working group called STRUBIAS. This working group has proposed that the inclusion of pyrolysis materials as Component Material Categories (CMC) in the forthcoming revised fertilizing regulation can enable potential biochar applications, namely, as a fertilizer, soil improver, growing medium, and non-microbial plant biostimulant. In their draft report, STRUBIAS concluded that no limitations were needed for the core process of pyrolysis. Nevertheless, product quality is seen as of extreme importance, and thus quality standards are still needed. This recommendation means that biochar regulations will be of an "output" nature, instead of the "input or throughput" kind [75].

The lack of proper biochar-related policies has resulted in the design of the voluntary biochar quality standards shown in Table 7. These certification schemes aim to provide quality and safety indicators for the use of biochar in agricultural applications only, leaving other potential applications out of their scope. Nonetheless, certification has the potential to promote industrial and commercial interest in biochar and further influence novel laws and regulations [73,74]. The main parameters covered by these three standardization procedures are described in Table 8.

The development of the EBC has led to the first steps being taken in controlling the quality and sustainability of biochar and its production. Depending on the development of the biochar sector, these voluntary certification schemes will need to be updated and revised over the next few years. The sustainability of biochar implementation in farming and industrial practice does not seem to be a major obstacle if certification standards such as the ones described in Table 8 are met. Nevertheless, meticulous quality control to prevent exceeding maximum allowed limits for toxic compounds (e.g., PAH, B(a)P, PCDD/F, heavy metals), strict process-based controls, and demanding requirements to demonstrate feedstock sustainability, can increase production costs in the EU. If those requirements become too excessive, the industry might be forced to look for other uses outside of agriculture, specifically high-added value applications (described in Section 3) [7].

Table 8. Overview of biochar certification schemes [73,74].

Parameter	Units	IBI-BS	EBC		BQM	
			Basic	Premium	Standard	High Grade
Organic C	%	≥10	≥50		≥10	
H/C	—	≤0.7	≤0.7		≤0.7	
O/C		—	≤0.4		—	
Moisture	%	—	≥30		≥20	
Ash		√	√		√	
EC	mS m^{-1}	√	√		Optional	
Liming	—	√	—		—	
pH		√	√		√	
PSD	mm	√	—		√	
SSA	m^2g^{-1}	—	√		Optional	
AWC	%	—	√		Optional	
VM		Optional	√		—	
Germination	-	Pass/Fail	Optional		—	
Total N	%	√	√		√	
P, K, Mg, Ca		Optional	√		Total P&K	
PAH	mg kg^{-1}, db	≤300	<12	<4	<20	
B(a)P		≤3	—		—	
PCB		≤1	<0.2		<0.5	
PCDD/F		≤17	<20		<20	
As	mg kg^{-1}, db (max.)	12–100	—		100	10
Cd		1.4–39	1.5	1	39	3
Cr		64–1200	90	80	100	15
Co		40–150	—		–	
Cu		65–1500	100		1500	40
Pb		70–500	150	120	500	60
Hg		1–17	1		17	1
Mn		—	—		—	3500
Mo		5–20	—		75	10
Ni		47–600	50	30	600	10
Se		2–36	—		100	5
Zn		200–7000	400		2800	150
B		√	—		—	
Cl						
Na						

Note: PSD—Particle Size Distribution; AWC—Available Water Holding Capacity; VM—Volatile Matter. The symbol √ refers to the required analysis for biochar (declaration).

5. Overview of Current Biochar Markets

Market information is key to assessing business opportunities for new products resulting from applied research. Biochar is currently emerging as a key carbon commodity in several applications and is traded globally in increasing amounts. The market can be segmented by process, feedstock, and application. From a technological point of view, slow pyrolysis currently dominates biochar production with a market share of over 70% and is anticipated to display significant growth opportunities in the upcoming years. In the last decade, new biochar applications have driven the growth of the biochar industry sector, especially in China, but also in the USA and Europe (Table 9).

At the European level, a recent report by the European Biochar Industry Consortium provides a valuable snapshot of the current state of the market (Figure 1A,B). Until 2015, the industry was very small with about 20 biochar production plants in operation, but market dynamics increased significantly from 2016 onwards with more than 50 new plants installed [77].

Table 9. Current biochar production in the top global markets.

Market	Current Biochar Production
China	>300,000 (up to 500,000) t/y and rapidly growing
USA	~50,000 t/y and growing
Europe	>20,000 t/y and growing
Australia	~5000 t/y and growing

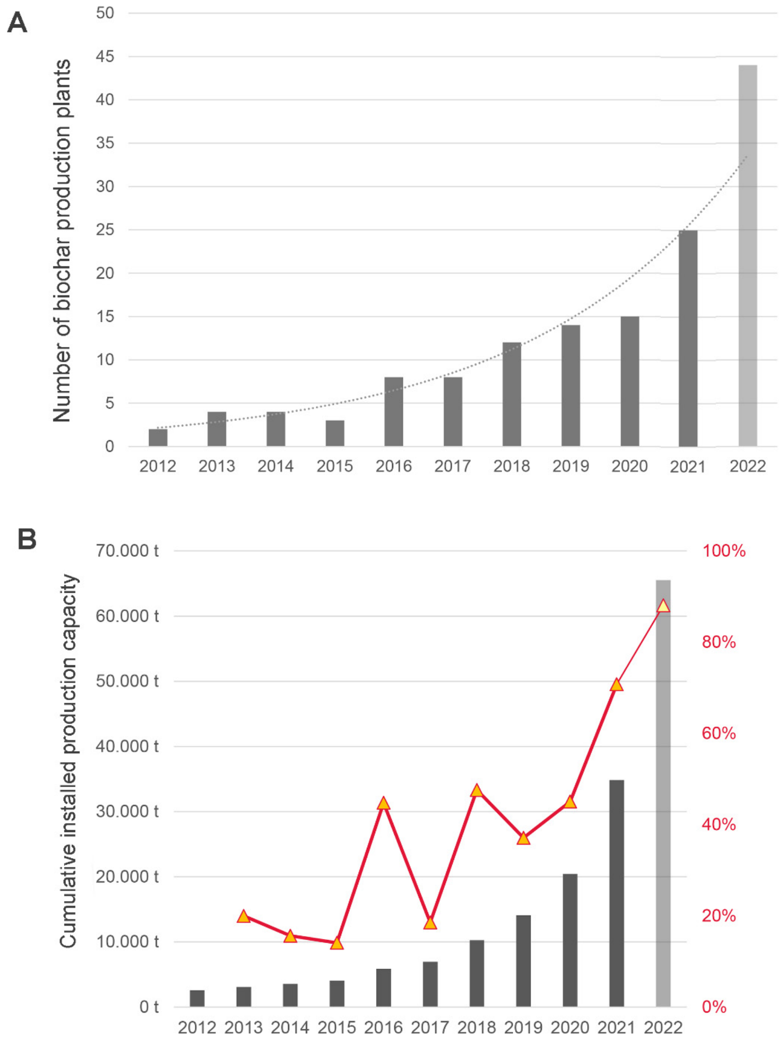

Figure 1. Current state of the European biochar market. (**A**) number of biochar production plants installed per year; (**B**) cumulative biochar production capacity (bars, expressed in t, left *y* axis) and growth rate (red line, expressed in %, right *y* axis) [77].

In 2021 alone, 25 new systems were commissioned, bringing the total number of plants to more than 100 and suggesting a rapid consolidation of the biochar industry in Europe. In terms of production capacity, the biochar market size achieved 35,000 tonnes in 2021 (actual production of 20,000 tonnes) based on substantial growth in the last decade. Indeed, growth rates for cumulative production capacity are expected to continue accelerating in 2022, with a projected three year compound annual growth rate (CAGR) of 67% between 2019 and 2022 [77]. With a global average biochar price of 800 euros per tonne [78], the current value of the European biochar market is estimated at almost 16 million euros, with good perspectives for continued growth into two digits. In the same period, Germany, Austria, Switzerland, and Scandinavian countries (mostly Sweden) dominated European biochar production, accounting for more than 75% of the market. Other countries, such as Spain, are also emerging, and opportunities abound [77]. Portugal, for example, has a significant potential to be an important player in the European biochar industry based on abundant feedstocks, technological know-how, and potential applications. Nevertheless, elementary market data is scarce and difficult to gather. As a result, the current state of the Portuguese market is largely unknown, with the industry dominated by a limited number of players. Ibero Massa Florestal and Biogreenwoods are the major biochar producers in Portugal for domestic and/or agricultural applications. Their products are widely available in retail and their activities are expected to expand in the next few years as biochar captures market share in traditional markets. However, demand is still limited by high prices due to reduced market competition and a lack of awareness among consumers.

6. Biochar Potential in Alentejo

Forest and agriculture management produce biomass wastes that may be used for biochar production. In Alentejo, both sectors generate more than 1.9 million tonnes of waste annually, with feedstocks such as corn stalks, vine prunings, olive prunings, eucalyptus, cork oak, and shrubs aggregating most production (Table 10). This biomass availability can be used to estimate the technical biochar potential in the region using slow pyrolysis as the technology of choice. To provide an estimate of biochar's potential in Alentejo, a 100% biomass utilization factor was considered, and the slow pyrolysis process conditions considered were the ones detailed in each reference for biochar yield (Table 10). However, the percentage of biomass used in biochar production would be considerably lower considering biomass competition for other uses and market constraints. Also, process conditions, particularly temperature, will have a significant impact on biochar mass yield and overall properties (important to define end-use).

Overall, the almost 2,000,000 tonnes of biomass waste harvested annually in the region can potentially produce 491,000 tonnes of biochar every year, a significant amount with an estimated economic value of more than 850 million euros. This theoretical market potential alone presents attractive investment opportunities, in particular when considering the future growth perspectives for the European biochar market.

In addition, biochar use in the region can provide several economic, environmental, and social benefits. Table 11 shows that Alentejo has a high potential for carbon drawdown provided by biochar production via slow pyrolysis.

The results in Table 11 should be interpreted as a theoretical approximation of biochar's potential benefits. Agricultural land application, which accounts for over 2,000,000 hectares in Alentejo, can be considered to effectively promote soil restoration, and improve water conservation and soil management. A biochar application rate of 5 tonnes per hectare would help improve SOM with a capacity of improving almost 100,000 hectares every year. Covering the whole agricultural land in the region would take 22 years, demonstrating that there is plenty of soil to receive the produced biochar, even at 100% utilization of biomass wastes.

Table 10. Technical biochar potential produced from the slow pyrolysis of the main wastes available in Alentejo.

Feedstock Type	Amount (kt/y) [79]	Biochar Yield (wt.%)	Biochar Production (kt/y)
Agricultural wastes			
Corn stalks	768.8	28.0 [80]	215.3
Rice straw	129.0	25.0 [81]	32.3
Vine prunings	296.1	30.0 [82]	88.8
Olive prunings	188.1	10.0 [83]	18.8
Fruit tree prunings	32.7	23.6 [84]	7.71
Forestry wastes			
Pine	84.5	21.0 [81]	17.7
Eucalyptus	124.4	22.0 [82]	27.4
Cork oak	130.4	24.5 [82]	32.0
Green herbaceous wastes	89.0	27.8 [85]	24.7
Shrubs	129.6	20.0 [82]	25.9
Total	1 972.6	-	490.9

Table 11. Estimated benefits of the potential application of biochar in Alentejo agricultural lands considering 100% of the technical biomass potential. Methodology from Pacific Biochar [86].

Parameter	Value	Remarks
Biochar application in agricultural land		
Biochar application rate (t/ha)	5	Biochar application rate from Chiaramonti and Panoutsou (2019) [87]
Land covered (ha/y)	98,104	
Time until 100% coverage (y)	22	Total agricultural land in Alentejo: 2.14 Mha [88].
Direct carbon sequestration		
Carbon sequestration potential, C (kt-C)	441.8	Direct carbon sequestration of 3.12 t-CO_2/t-biochar. Calculated from Lehmann et al. (2015) [89]
Carbon sequestration potential, CO_2 (kt-$CO_{2\text{-eq}}$)	1529	
GHG emissions reduction (ER)—ancillary		
GHG ER, Enteric fermentation (kt-$CO_{2\text{-eq}}$)	348.9	GHG emission reductions of 22%, 20%, and 36% for enteric fermentation, manure management, and soil, respectively [90,91].
GHG ER, Manure management (kt-$CO_{2\text{-eq}}$)	37.60	
GHG ER, Soil (annual) (kt-$CO_{2\text{-eq}}$)	11.20	
GHG ER, Combined ancillary benefits (kt-$CO_{2\text{-eq}}$)	397.7	
GHG ER + Direct sequestration (kt-$CO_{2\text{-eq}}$)	1927	
Cost per t of CO_2 drawdown		
Direct sequestration (€/t-$CO_{2\text{-eq}}$)	257	Considering an average biochar price of 800 €/t [78].
GHG ER, Ancillary (€/t-$CO_{2\text{-eq}}$)	987	
Total of direct and ancillary (€/t-$CO_{2\text{-eq}}$)	204	

Table 11. *Cont.*

Parameter	Value	Remarks
Water conservation		
Increased WHC (million m^3)	6.20	Considering that soil WHC improves by 62 m^3/ha (+ 0.25–1% SOM, top 15 cm) [92]. Soil bulk density is taken from INFOSOLO database [29].
Days of water use in Alentejo (d)	46	Residential water consumption is taken from ERSAR [93].
Nitrogen management		
Maximum nitrogen retention capacity (kt-N)	88.36	N retention capacity of 0.18 g-N/g-biochar from Hestrin et al. (2019) [94].
N Leaching reduction, agricultural land (t-N/y)	127.0	N-leaching from agriculture in Alentejo: 10 830 t-N/y [95,96].

Note: SOM—Soil Organic Matter; WHC—Water Retention Capacity.

On the other hand, Portugal plans to achieve carbon neutrality in 2050 in line with EU climate targets. Biochar can contribute to achieving this goal by promoting carbon drawdown either by direct sequestration or by emissions reduction via ancillary benefits. Specifically, carbon sequestration potential derived from biochar application was estimated to achieve 1,500,000 tonnes-$CO_{2\text{-eq}}$, a value equivalent to roughly 8% of Alentejo's total GHG emissions in 2017. In terms of ancillary emission reduction, a recent meta-analysis study found that biochar can reduce soil N_2O emissions by an average of 38% [90]. Using these numbers, the potential GHG emissions reduction of applying biochar in agricultural soils at 5 tonnes per hectare was estimated at 11,000 tonnes-$CO_{2\text{-eq}}$. [90]. This number represents a reduction in one year only, which means that the continuous application of biochar would reduce soil emissions even more. Besides, animal manure management and enteric fermentation related to animal feeding are also significant contributors to GHG emissions. Considering only the emissions from the dairy industry, biochar has been reported to provide a 20% reduction in GHG emissions from manure management for a total of 38,000 tonnes-$CO_{2\text{-eq}}$ in Alentejo [86]. Concerning enteric fermentation, biochar feed supplementation at 0.6 wt.% has been linked with emissions reductions in the order of 22%, resulting in savings of 349,000 tonnes-$CO_{2\text{-eq}}$ [91]. Nevertheless, these benefits come at a cost. Considering the average price of one tonne of biochar at 800 euros, the combined GHG emission reduction can only be accomplished at 204 euros per tonne-$CO_{2\text{-eq}}$.

Finally, biochar soil amendment also leads to water conservation and prevents nitrogen leaching. Biochar's ability to improve soil WHC is estimated at roughly 250 cubic meters in each hectare of soil for a 1% increase in SOM [92]. Based on these figures, the potential annual increase in the WHC of Alentejo's soils was calculated at about 6 million cubic meters, which is equivalent to 46 days of residential water use in the region. In terms of preventing N-leaching, Hestrin et al. (2019) recently explored the mechanisms involved in nitrogen retention on biochar and reported a total N-retention capacity of 0.18 g-nitrogen/g-biochar. This capacity would translate to an additional 88,000 tonnes of nitrogen (0.9 tonnes per hectare) retained in the soil across the region, a very interesting theoretical goal [94]. Moreover, the Portuguese Environmental Agency estimated in 2012 that nitrogen leaching in the regions' groundwaters reached 10.8 tonnes. Related to N-leaching, Borchard et al. (2019) found that biochar's impact on soil nitrogen dynamics can reduce nitrogen leaching by 25%, meaning that more than 120 tonnes of N could be prevented from entering Alentejo's groundwaters [90]. Overall, these results indicate that biochar has an enormous potential to effectively mitigate several environmental concerns related to agricultural lands in the region. However, several barriers are likely to hinder biochar market development in Portugal. Educational awareness of biochar's attributes for agriculture is still lacking, and costs may also be too high for farmers to consider using biochar to increase crop productivity. Indeed, increased crop income is unlikely to bring sufficient economic profitability, and additional measures to reward biochar's ecosystem services should be put forward. Incentives associated with the direct carbon sequestration benefits of biochar would play a decisive role in developing commercial markets but require policy development at the national and European levels. New methodologies and legislative frameworks need to be established to support farmers and increase biochar application in agriculture.

7. Conclusions

Biochar has the potential to be used in different markets as a new, inexpensive, and environmentally friendly carbon material. Research on biochar production and application pathways is well underway, although a few knowledge gaps exist, particularly regarding increasing process sustainability and biochar's long-term effects in its final end-use (e.g., carbon sequestration). According to the reviewed literature, biochar properties depend on different factors, such as feedstock type, production process, and process conditions. This variability is also the reason why it is possible to design appropriate biochars with the right properties for a given application, which is one of the major strengths of biochar as a product. Considering the current industry status, a SWOT analysis with the major positive effects (strengths and opportunities) and major negative effects (weaknesses and threats) of biochar production and application can provide a more strategic vision of biochar use in a regional context (Table 12). From the analysis, there are several market opportunities for industry development but also some important market barriers. For example, the lack of legislation and policy regarding biochar production and use are both widely considered to limit market demand. Nevertheless, the existence of certain policy initiatives (albeit mostly at the regional level in the EC) and voluntary certification schemes shows the potential to drive biochar production faster and increase biochar acceptance in several markets. Major legislation is being formulated, but with a particular focus on biochar's agricultural applications, particularly as a fertilizing agent.

Table 12. SWOT analysis for developing the biochar industry in Alentejo.

Strengths	Weaknesses	Opportunities	Threats
• Feedstock availability • Several potential applications • Established production technologies • Valuable byproducts • Integration in biomass heating systems • Upscaling • Tailor-made biochar • Biochar provides synergistic solutions to problems that concern policymakers: food and energy security, climate and sustainability, and land remediation	• Low market awareness and limited demand • Lack of specific policies and legislation • High selling prices • Knowledge gaps: long-term carbon sequestration, contaminants release, and impact of biochar on ecological systems.	• Potential to attract capital investment due to synergies with renewable energy or waste mitigation • Potential for mobile biochar production • Biochar can benefit from restricting regulations regarding air, water, and soil pollution, GHG emissions, or reducing organics sent to landfill • Versatile material • Rural and regional development	• Large array of physicochemical characteristics • Quality control • Improper communication regarding biochar production, characteristics, and applications • Lack of awareness regarding the benefits of biochar • Potential competition with other biofuels for biomass resources

Slow pyrolysis is the most implemented process for biochar production. This technology is expected to show significant growth opportunities in the next few years in parallel with the development of the biochar market throughout Europe. Although the Portuguese market is still limited and largely unknown, the country shows potential to be an important player in the European market, mostly due to its abundant feedstocks, technological know-how and diversity in potential biochar applications. Nevertheless, elementary market data is currently scarce and difficult to gather.

Alentejo is a good example of Portugal's potential for biochar production and application. An estimate of the regional market potential can be obtained by gathering the various biomass feedstocks from which biochar can be sustainably produced. Considering a theoretical biomass waste utilization rate of 100% (for the main agricultural and forestry wastes), under given slow pyrolysis conditions, estimates indicate a maximum biochar potential of almost 500,000 dry tonnes per year. This biochar has an estimated economic value of more than 850 million euros and can potentially be traded in several market segments. However, a better picture of potential markets should be provided by a thorough analysis of the current value of the market segments in which biochar can realistically gain market share (e.g., wastewater remediation, or addition in composite materials for the construction sector). Agricultural applications probably hold the greatest near-term potential in Alentejo showing relevant estimated benefits as a carbon reductive soil amendment. These benefits include emissions reduction by combined direct and ancillary effects of almost 2,000,000 tonnes-$CO_{2\text{-e}}$ which is equivalent to 10% of total Alentejo GHG emissions. Furthermore, biochar was also estimated to potentially retain an additional 6,000,000 cubic meters of water in regional soils and possibly reduce nitrogen leaching by 127 tonnes/year to the region's groundwaters. Finally, soil nitrogen retention would also be increased by 88,000 tons thus helping agricultural soil restoration.

Biochar shows the potential to be an effective strategy to reduce important environmental concerns related to agricultural lands in Alentejo. However, more should be done to encourage farmers to use biochar for crop improvement and enable society to gain from its positive externalities. In particular, the biochar industry can have a positive influence on climate change, local food and energy security, rural employment and regional growth whilst promoting the development of a new range of marketable products and services. Specific measures should be put forward to effectively accelerate biochar market development at the regional level and beyond.

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