Geoderma Regional 33 (2023) e00634

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Biochar soil amendment as carbon farming practice in a Mediterranean environment

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ARTICLE INFO

Keywords:
Carbon cycle
Soil quality
Field trials
Soil water holding capacity
Crop yield
Luvisols

ABSTRACT

Carbon Farming is a new approach for land management that allows the sequestration of carbon in the soil and plants, mitigating the emission of greenhouse gases. It includes a set of eco-friendly strategies. Among them, increasing of carbon content through the application of biochar seems to be particularly promising for the Mediterranean area, where erosion and loss of organic matter is a relevant problem for agricultural production. Although soil amendment with biochar has received significant and increasing attention during the last decade, few studies have been focused on the Mediterranean basin. In this review, state of the art use of biochar as carbon farming practice in the Mediterranean region from the legislative, policy and scientific point of view has been discussed. Throughout the review, a description of the main results obtained from 36 studies carried out at 23 different field locations, with regard to carbon dynamics, soil water holding capacity (WHC) and crop yield has been reported. As a concluding remark, it is observed that biochar has good potential to store carbon in Mediterranean soils; it has a good proportion of recalcitrant carbon and can effectively improve soil water content under limited water conditions such as during drought and summer.

However, long-term field studies on various Mediterranean soils should be performed in order to reach valid conclusions on the effects of biochar on the plant-soil system in the Mediterranean basin. In this context, it is essential to report a set of basic parameters to link the main characteristics of biochar, and its effects on soil and plant productivity.

1. Introduction

Carbon farming is a new terminology to describe farming land management practices, capturing CO_2 from the atmosphere and storing it in natural sinks such as soil and living biomass. It has been proposed as an effective measure to mitigate greenhouse gas (GHG) emissions in several countries (Parikh and Winfield, 2020; Winfield, 2020). Carbon farming also refers to the business model that aims to upscale climate mitigation by incentivizing farmers to implement climate-friendly farm management practices (EC, 2021b).

McDonald et al. (2021) have classified carbon farming interventions into five classes:

1) Peatland rewetting and restoration
2) Agro-forestry system establishment and maintenance
3) Conservation, and enhancement of soil's total organic carbon (TOC)
4) Livestock and manure management
5) Nutrient management on cropland and grassland

Among all these strategies, increasing TOC by different agronomical practices (e.g., organic amendment, cover cropping, improved crop rotations) is a promising strategy for both climate change mitigation and organic carbon retention. This is especially so in the Mediterranean area where erosion and the consequent loss of organic matter are relevant problems for agricultural production (Yaalon, 1997; Zdruli et al., 2007).

In this regard, soil amendment with biochar has received substantial and increasing attention during the last decade. In fact, several recent reviews focused on the influence of biochar on soil properties and

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https://doi.org/10.1016/j.geodrs.2023.e00634
Received 12 November 2022; Received in revised form 20 March 2023; Accepted 21 March 2023

nutrient cycles (Agegnehu et al., 2017; Gul and Whalen, 2016; Lehmann et al., 2011; Pan et al., 2013; Vijay et al., 2021; Yang et al., 2021), and gas emissions and carbon sequestration (Kalakodio et al., 2018; Li et al., 2018; Majumder et al., 2019; Siedt et al., 2021; Tisserant and Cherubini, 2019).

According to the International Biochar Initiative (IBI), biochar is a charcoal whose primary application is as a soil amendment for increasing soil fertility while ensuring long-term carbon storage (IBI, 2012; Montanarella and Lugato, 2013). Specifically, biochar is a carbon-rich by-product from pyrolysis of organic material whose potential to improve soil properties and functions (e.g. improving soil fertility, soil stability, water retention and enhancing carbon sequestration) have been extensively studied (Schmidt et al., 2021; Siedt et al., 2021; Verheijen et al., 2010). As outlined in the literature, the effects of biochar in agriculture depends on a number different factors including its origin and production, crop and soil types, the applied quantities and climatic conditions (Chiaramonti and Panoutsou, 2019). Furthermore, some authors reported concerns relating to the soil safety over a long-term period, mainly due to the mechanisms affecting organisms' health (Brtnicky et al., 2021). Most of these studies were restricted to tropical, sub-tropical and temperate climate zones (Chagas et al., 2022; Vaccari et al., 2011), while few studies considered the Mediterranean region

Table 1
European and National legislations on Biochar.

Indicator	Unit measure	Italian Regulation 75/2010[1]	EU Fertilizers regulation 2019/1009[2]	
		BIOCHAR FROM PYROLYSIS OR GASIFICATION	CMC 14 PYROLYSIS AND GASIFICATION MATERIALS	PFC 1 (fertilizer), PFC 3 (soil improver), PFC 4 (growing media)[7]
Materials		Residues of vegetable origin coming from agriculture and from forestry, as well as from olive pomace, pomace, bran, kernels, and shells of fruit, not treated wastes of wood processing, by-products of related activities.	1. Living or dead organisms or parts of thereof[3] 2. Vegetable waste from the food processing industry and fibrous vegetable waste from virgin pulp production and from production of paper from virgin pulp 3. Processing residues from the production of bioethanol and biodiesel 4. Biowaste resulting from separate biowaste collection at source 5. Pyrolysis and gasification additives	
Process		Pyrolysis or gasification	Thermochemical conversion under oxygen-limiting conditions ($t > 180$ °C for at least two seconds)	
Total carbon (biological source)	%	>60 Class 1 $30 < TC \leq 60$ Class 2 $20 \leq TC \leq 30$ Class 3		
Ashes	%	<10 Class 1 $10 \leq$ Ashes≤ 40 Class 2 $40 <$ Ashes≤ 60 Class 3		
Electrical conductivity	mS/m	≤ 1000		
pH	–	$4 < pH < 12$		
Water content	%	≥20%[4]		
Molar H/C_{org}	–	≤0.7	<0.7[5]	
PAH16	mg/kg ds	<6	≤6	
PCCD/F	ngWHO TE/kg ds	<9	≤20	
PCB	mg/kg ds	< 0,5	≤0.8	
Cl-	mg/kg ds		≤30	
Tl	mg/kg ds		≤2[6]	
Pb	mg/kg ds	≤140		≤120
Cd	mg/kg ds	≤1.5		≤1.5–2-3
Ni	mg/kg ds	≤100		≤50–100
Zn	mg/kg ds	≤500		≤500–800-1500
Cu	mg/kg ds	≤230		≤200–300-600
Hg	mg/kg ds	≤1.5		≤1
Cr VI	mg/kg ds	≤0.5		≤2
As	mg/kg ds			≤40
Biuret	mg/kg ds			Must not be present-12[8]
Perchlorate	mg/kg ds			≤50[9]

1 Reorganization and review of the fertilizer regulations (Riordino e revisione della disciplina in materia di fertilizzanti) Decreto legislativo 75/2010.
2 *Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003,* 2022.
3 Materials not allowed: Mixed municipal waste Sewage sludge, industrial sludge or dredging sludge, animal by-products.
4 Powdered products.
5 Testing to be performed in the dry and ash-free fraction for materials that have an organic carbon content of <50%.
6 In case >5% of additives relative to the fresh weight of total input material have been applied.
7 PFC 1 is divided into PFC 1(A) organic fertilizer; PFC 1 (B) organo-mineral fertilizer; PFC 1(C) inorganic fertilizer. PFC 3 is divided into: PFC 3(A) organic soil improver and PFC 3(B) inorganic soil improver.
8 Biuret must not be present in PFC 1(A). The limit of 12 is for PFC 1(B) and PFC 1 (C).
9 Limit for perchlorate is only for PFC 1(C).

(Zabaniotou and Stamou, 2020), which is partially affected by desertification (Zdruli et al., 2007). To our knowledge only one review on the use of biochar for improving crop growth in the Mediterranean is present in the literature (Zabaniotou and Stamou, 2020). However, no specific review has focused on biochar-based carbon farming practices in the Mediterranean area.

As such, this review reports on the state-of-the-art knowledge about biochar soil amendment on Mediterranean soils, with a final emphasis on a POR-FESR research project ("Biochar Latium"), funded by Lazio Region, and related issues.

2. The use of biochar as a carbon farming practice in EU legislation and policy

In general, the regulatory framework for biochar use in agriculture is relatively new, having only been in force in the last few years.

Biochar has been added by the Commission Delegated Regulation (EU 2021/2088, 2021a) into the current EU Fertilizer Regulation (EU/2019/1009), which promotes the production and use of bio-fertilizers from recycled biowaste in the EU market. This legislation framework, which applies to the CE fertilizer market, sets limit values for contaminants and heavy metals in EU fertilizing products, recategorizing the well-known fertilizer types into new product function categories (PFC). As a result, recycled products can be valorized into CE marking fertilizers for the first time, with free marketability throughout the EU. Moreover, component material categories (CMC) were introduced, with specific material. and production requirements. Biochar has been categorized as CMC 14, as "Pyrolysis and gasification materials", with specific requirements about process production, feedstocks and product quality, and contaminant concentrations (Table 1). Biochar has been also authorized in organic agricultural production (EU 2021/1165, 2021b), with use according to EU 2019/1009 as a pyrolysis product made from a wide variety of organic materials of plant origin and applied as a soil conditioner only from plant materials.

Biochar application as a fertilizer is also regulated at national level in some EU Member States (e.g., Germany, Denmark, The Netherlands, Norway, Italy) (Meyer et al., 2017), with only Italy sitting within the Mediterranean area (Garcia et al., 2022). In Italian regulations, where biochar was added as a soil improver in 2015 (Decree, 2022), technical specifications about process, feedstock and product quality are also defined, and limits for pH and electrical conductivity were added. Moreover, a different categorization of biochar quality based on chemical components was defined (Table 1). It should be noted that recently (October 2022) biochar has also been authorized for use in organic agriculture (Decree, 2022), with the only difference in the limit of PAH16 allowed in biochar (<4 mg/kg).

In December 2021, the European Commission adopted the "Communication on Sustainable Carbon" (EC, 2021c). This set out actions to address current challenges on carbon farming and to reward land managers for taking up practices leading to carbon sequestration, while considering the strong benefits on biodiversity.

Governments must adopt measures that build more resilient economic systems, incentivizing "no-regret" measures, such as agro-ecological farming approaches, which valorize local organic by-products and simultaneously reduce the reliance on energy-intensive synthetic fertilizers (Benton et al., 2022; Galanakis et al., 2022). The transition to organic farming should be, however, a gradual process accompanied by the proper technology (precision agriculture, information technology) and through appropriate training of farmers. Only in this way can the process be sustainable from an economic perspective, possibly avoiding a crisis such as the one faced by Sri-Lanka in its shift to organic farming (https://time.com/6196570/sri-lanka-crisis-organic-farming/).

Recently, in a global meta-analysis study, Shakoor et al. (2022) highlighted that combining biochar with wheat cultivation, and to a lesser extent with maize, would be the best way to increase crop productivity while reducing GHG emissions, with respect to other soil conservation practices such as no-tillage and manure application. Notwithstanding the evidence of these potential benefits in TOC sequestration practices, farmers need urgent policies and incentives for their adoption (Jat et al., 2022). Although farmers are aware of the benefits of applying carbon farming, the use of biochar remains a technique least likely to be adopted (Dumbrell et al., 2016), due to the uncertainty of policies and carbon price and the unclear impact of biochar amendment on productivity and profitability. Regarding concerns relating to the economic feasibility of biochar application, Dokoohaki et al. (2019) concluded that for corn farmers the application of biochar can be acceptable from a revenue point of view, with respect to wheat and soybean cultures in the US market, suggesting the need for carbon credits for large application of biochar. Similar conclusions have been drawn by Chiaramonti and Panoutsou (2019) for sunflower cultivation in dry marginal lands in Italy: the authors highlighted that the co-application of biochar and compost generated a sufficient income given the support measures based on current EU policies. However, the need for economic incentives for a transition to low-carbon agriculture has been extensively highlighted in scientific literature, not only at Mediterranean level, but also at EU and international level (Borychowski et al., 2022; Verde and Chiaramonti, 2021).

3. Mechanisms involved in the biochar and soil carbon cycle interaction

Biochar is a carbon-rich material in which carbon is arranged into aromatic structures and occasionally piles of graphite-like layers (Zimmerman, 2010). Thanks to these properties, biochar, when applied to soil, is expected to remain stable for many years (from 100 to 4000 years) (Lehmann et al., 2006). However, carbon added by biochar is not completely inert and can be slowly mineralized through biotic and abiotic processes (Enders et al., 2012).

To clarify the importance of soil–biochar interactions in the carbon cycle, in this section the impact of biochar on the native soil organic matter (SOM) mineralization, protection and stabilization processes is discussed. Two aspects are illustrated in detail:

1. SOM, mineral and biochar interactions
2. Biochar and soil microorganism interaction

3.1. Soil organic matter, mineral and biochar interactions

Biochar acts as a binder among the components of soil aggregates and can thus improve soil stability (Du et al., 2017). This property relies on the interaction between biochar and clay minerals through surface hydrophilic–hydrophobic connections, following the conceptual model of organo-mineral interactions proposed by Kleber et al. (2007). At the same time, biochar interacts with soil mineral multivalent cations to form a mineral organic matter complex, which enhances the stability of soil aggregates and long-term carbon sequestration (Chen et al., 2019; Luo et al., 2013). This phenomenon is strictly dependent on the soil texture, as biochar has minimal impacts on aggregation in coarser textured soil (Awad et al., 2013; Lehmann et al., 2011). Furthermore, electron donor-acceptor interactions can occur between aromatic compounds of biochar and mineral surfaces, as well as between two aromatic compounds, as described by Keiluweit and Kleber (2009). On the other hand, biochar can act as the core component of aggregate and, like other particulate organic components, can improve microbial activity (Lehmann et al., 2011). Biochar can also indirectly influence the process of soil aggregation by affecting microbial activity as described in section 3.2, plant root architecture and secretion, and root symbiotic relationships with fungi. In this regard, Cross and Sohi (2011) reported that the interactions between biochar and mineral complexes and between biochar and mycorrhizal fungi enhance the formation and stability of soil aggregates.

Biochar degradation in soil has been reported to fit well into a double exponential model with a first phase in which the labile biochar fraction degrades rapidly (Thies and Rillig, 2009) and a second one in which the recalcitrant portion (aromatic and more condensed chemical structures) oxidizes more slowly (Ventura et al., 2019). The addition of easily oxidizable organic matter through biochar influences the mineralization rate of the original organic matter (positive priming effect). The increase of the mineralization rate is termed the "positive priming effect" while the opposite one is the "negative priming effect" (Bingeman et al., 1953; Kuzyakov, 2010). The intensity and direction of the priming effect may vary, depending on the materials used for the biochar production (Spokas et al., 2009), soil texture, SOM composition and other factors. For example, Zimmerman (2010) has found that adding grass wood biochar pyrolyzed at 250–450 °C results in a very strong priming effect, while using woody plant biochar pyrolyzed at 450–700 °C has no strong priming effect due to the different degrees of carbonization. Conversely, other authors (Keith et al., 2011; Spokas et al., 2009; Zimmerman et al., 2011) observed a "negative priming effect". This was attributable either to the SOM absorption within the pores and surface of the biochar, or to the use of organic carbon released from the biochar as primary carbon source to enhance the growth, activity, and respiration of soil microorganisms instead of mineralization of original SOM (Jones et al., 2011; Li et al., 2021; Yang et al., 2022). In this regard, it has been shown that the adsorption affinity of biochar surfaces for SOM increase with rising pyrolysis temperature (Kasozi et al., 2010). A meta-analysis carried-out by Maestrini et al. (2015) highlighted that pyrogenic organic matter positively primes the native SOM in the first 20 days while a negative priming effect appears in the later stages. Furthermore, biochar characterized by a low carbon content seems to induce a higher positive priming effect on native soil organic carbon (Maestrini et al., 2015).

3.2. *Biochar and soil microorganism interaction*

The soil microbial community shows different responses to the addition of biochar, in terms of abundance, composition, activity and diversity (Chen et al., 2018; Prayogo et al., 2014; Yan et al., 2021). Many studies indicate that soil biochar amendment stimulates the growth of microorganisms in a short period, increasing microbial abundance and activity (Lehmann et al., 2011; Liang et al., 2010). The increased microbial biomass is mainly attributed to the physical structure of biochar rather than the added oxidizable carbon source by biochar (Lehmann et al., 2011; Li et al., 2021; Yan et al., 2021; Yang et al., 2022). Indeed, the pores and particles of biochar provide a niche of both food and physical habitat for microorganisms; promoting their colonization, growth, and reproduction (Al-Wabel et al., 2018). Further, biochar can help to mitigate climate change effects through an increase in the resistance of soil microbial community and enzyme activity to drought (Liang et al., 2014; Paetsch et al., 2018). Therefore, adding biochar to soil could be particularly important in Mediterranean regions already experiencing extreme climatic events (e.g., prolonged drought periods, heatwaves, and torrential rain), and which have increased aridity (Peñuelas et al., 2018).

Studies in field trials in the Mediterranean basin that evaluated the effects of biochar on microbial community are contradictory. For example, Ameloot et al. (2014) reported that, after one to four years, biochar application did not affect soil microbial activity and abundance. Similarly, Baronti et al. (2014) did not observe negative effects on the microbial community in a vineyard after five years of biochar application to the soil. On the contrary, in a six year study carried out in a Mediterranean agro-ecosystem (Moreno et al., 2022), a significant effect on composition and diversity of soil bacterial community was observed after biochar application, as summarized in Table 2. Moreover, substantial changes in soil microbial activity that correlated with increased use of recalcitrant carbon and decreased use of carbohydrate carbon were observed by Giagnoni et al. (2019), who showed the results of a long field trial (seven 7 years) on the amendment of a vineyard with biochar.

4. Biochar soil amendment in the Mediterranean Basin

4.1. *Agricultural soils in the Mediterranean*

The Mediterranean basin can be considered a single fragile ecosystem, particularly vulnerable to soil degradation (Ferreira et al., 2022), which includes many natural features and a great variety of soils. Within the EU, the Mediterranean basin has the overall highest erosion rates (Panagos et al., 2020), the lowest levels of SOM (Aguilera et al., 2013) and severe salinization problems (Stolte et al., 2016). It also has high abundance of shallow soils (Lagacherie et al., 2018), strong, increasing, human pressures (Guittonny-Philippe et al., 2014) and high climate change vulnerability (Intergovernmental Panel on Climate Change, 2019). One of the most used criteria to establish whether a geographical area can be classified as Mediterranean climate is the xeric soil moisture regime of the USDA Soil Taxonomy (2006) describing dry conditions (SSS, 2010) and a temperature regime which is *thermic* (mean annual soil temperature of 15°-22 °C) or occasionally *mesic* (8°-15 °C) (Verheye and Rosa, 2005).

European Mediterranean soils are quite diverse and reflect variations in climate, landscape, vegetation, time, and anthropogenic activities. In addition to the Rhodic and Chromic Luvisols (IUSS WRB, 2022) (well-known as "Terra Rossa"), the Mediterranean soil classification may vary from Regosols or Leptosols to Cambisols and Fluvisols (Ferreira et al., 2022; IUSS WRB, 2022; Zdruli et al., 2010). Cambisols are common in wide areas of the Iberian Peninsula and in most of the central and western Mediterranean islands, as well as in most parts of the Italian Peninsula. Leptosols are predominant in many areas of the countries influenced by the Aegean Sea, as well as some other parts of the eastern Iberian Peninsula. Luvisols are predominant in some areas of the regions influenced by the Marmara Sea, regions affected by the eastern part of the Ionian Sea or some areas of the central and western Iberian Peninsula (Rodeghiero et al., 2011). The typical karstic ecosystem of the Mediterranean area is mainly due to the dominance of the limestone and dolomites as parent materials (Zdruli et al., 2010).

Only 14% of the Mediterranean region (850 million hectares) is suited for agricultural production, the rest being devoted to pastures, wetlands, forests, shrubs, urban zones, badlands, rocky areas, and deserts (FAO, 2020). Despite Mediterranean countries being the European leaders for olives, fruit and vegetables production (Eurostat, 2019), the average land footprint per capita (i.e., the area of land needed per unit product) is among the highest in Europe due to extensive production forms adopted across the Mediterranean region, characterized by complex agro-sylvo-pastoral mosaics (European Commission, 2019).

The major soil threats in the Mediterranean region are linked with physical, chemical and biological soil degradation processes. Among these is soil sealing, which refers to soil that is permanently covered due to urbanization; wind and water soil erosion, which can reach very high rates (>2 t ha^{-1}) in agricultural land; OM loss mainly attributable to conversion of natural vegetation, grasslands and forests to cultivated land, and soil contamination (i.e., heavy metal and pesticide residues). These are driven by human activity are the most important major soil threats (Ferreira et al., 2022). Other causes of land degradation in the Mediterranean region include, loss of biodiversity; nutrient scarcity; flood; salinization; chemical pollution; contamination; overgrazing and degradation of vegetation cover, and unsustainable irrigation practices (Zdruli et al., 2007).

In this scenario, endorsing proper policies for soil protection, sustainable land management and land use planning in the Mediterranean region is an important requirement for the future, in line with international agreements such as the United Nations Convention to Combat Desertification (UNCCD) or the Biodiversity Convention.

Table 2
The effect of biochar in soils of Mediterranean basin: cases studies in field trials (pot experiments not included).

	Location	1.Biochar feedstock, pyrolysis temperature and pH 2.Application rate 3.Target crop	1. Soil classification 2. Soil characteristics	Time span of the study	Impact of BC application*	References
1	Beano, Italy	**1.** Coppiced woodlands $T = 500$ °C **2.** 2×10 t ha^{-1} **3.** *Zea mais*	**1.** Classification non provided **2.** Texture: silt loam Control soil: pH (KCl) = 7.24 Organic Carbon (OC) content = 1.43%	4 years	**Soil carbon:** no differences in organic C. **Productivity:** no data. **Other effects:** no differences in N content and C/N ratio, no significant shifts in microbial community composition, dehydrogenase activity and β-glucosidase. Soil pH after BC application: no change in comparison with control.	Ameloot et al., 2014
2	Rivignano, Italy	**1.** Pruning orchard T = 500 °C **2.** 30 t ha^{-1} **3.** *Zea mais*	**1.** Classification non provided **2.** Texture: clay loam Control soil: pH (KCl) = 7.71 OC content = 0.66%	7 months	**Soil carbon**: higher organic C content (OC content: 1.15% in BC treated soil). **Productivity:** no data. **Other effects:** increased C/N ratio, no significant shifts in microbial community composition and β-glucosidase.lower dehydrogenase activity. Soil pH after BC application: no change in comparison with control.	Ameloot et al., 2014
3	Rocca Bernarda, Italy	**1.** Pruning orchard $T = 500$ °C **2.** 30 t ha^{-1} **3.** *Vitis vinifera*	**1.** Classification non provided **2.** Texture: silt loam Control soil: pH (KCl) = 7.51 OC content = 1.18%	2 years	**Soil carbon**: no differences in organic C. **Productivity:** no data. **Other effects:** no differences in N content, increased C/N ratio, no significant shifts in microbial community composition and β-glucosidase**.** Lower dehydrogenase activity. Soil pH after BC application: 7.39.	Ameloot et al., 2014
4	Montepulciano, Italy	**1.** Orchard pruning $T = 500$ °C Slow pyrolysis pH = 9.8 **2.** 16.5 t ha^{-1} (**B**) and 33 t ha^{-1} (**BB**) in two times (16.5 in 2009 + 16.5 in 2010). **3.** *Vitis vinifera*	**1.** Classification non provided **2.**Texture: sandy-clay-loam pH = 5.37 OC content = 4.7 g kg^{-1}	2, 5, 7, and 10 years	**Soil carbon**: TOC increased after 7 years from application (a 13% and a 19% in the 1.5 and 33 t ha^{-1} application rates, respectively). After 7 years significant changes were observed towards a higher utilisation of recalcitrant C and less use of carbohydrate C by microbial communities. **Productivity:** harvesting during 4 years from BC application showed a higher productivity, up to 66%, of treated plots with respect to their controls. No significant differences in grape quality parameters. **Other effects:** relative increase in available soil water content compared to control soils after 2 years (from 3.2% to 45% in the 1.5 and 33 t ha^{-1} application rates, respectively). Decrease of soil bulk density. No negative impacts on soil microbial communities, no retention of toxic compounds (IPA and heavy metals) after 5 years. The effects of BC on soil fertility and functions were still evident 7 years after its application: the pH and total P were substantially increased; a change in the VOCs emission profile was reported. Significantly increase of 7% of the soil pH in B treatments and of 11% in BB treatments in comparison to control plots after 10 years; the ecophysiological measurements indicated an increase in soil water content and a significant increase in the water status of the plants in the plots treated with BC. Soil pH after BC application: 17% and 26% 5 years after biochar appliance in B and BB treatments respectively;7% and 11% 10 years after biochar appliance in **B** and **BB** treatments respectively.	Baronti et al., 2014 Genesio et al., 2015; Maienza et al., 2017; Giagnoni et al., 2019; Baronti et al., 2022; FAO and ITPS., 2021
5	Pistoia, Italy	**1.** Coppiced woodlands T = 500 °C Slow pyrolysis pH = 7.2 **2.** 30 and 60 t ha^{-1} in two growing seasons **3.** *Triticum aestivum cv Neolatino*	**1.** Classification non provided **2.** Texture: silty loam pH = 5.2 OC content = 21 g kg^{-1}	3 and 14 months	**Soil carbon**: BC can be successfully used to sequester atmospheric CO_2 in wheat cultures: the addition of 30–60 t ha^{-1} of BC was equivalent to 92–184 t of atmospheric CO_2 transferred into the soil. The treatment did not determine significant variations in total organic C, extractable organic C and microbial C. **Productivity:** occurrence of a significant and consistent positive effect up to 30% on growth and yield, without significant differences between the two BC treatments. The yield quality was maintained.	Castaldi et al., 2011; Vaccari et al., 2011; Rutigliano et al., 2014

(*continued on next page*)

Table 2 (*continued*)

	Location	1.Biochar feedstock, pyrolysis temperature and pH 2.Application rate 3.Target crop	1. Soil classification 2. Soil characteristics	Time span of the study	Impact of BC application*	References
					Other effects: the BC treatments showed minimal impact on microbial parameters and soil greenhouse fluxes. Soil pH after BC application: 3 months, 6.27 (30 t ha^{-1}) and 6.75 (60 t ha^{-1}); 14 months, no change.	
6	Gallignano, Italy	**1.** Mix of beech pine and fir wood T = ~850 °C **2.** 60 t ha^{-1} **3.** *Triticum aestivum*	**1.** Inceptisol (USDA) **2.**Texture: loam pH = 8.13 Soil Organic Matter SOM = 1.5%	2 years	**Soil carbon**: doubling of the soil total organic carbon that was maintained during the 2 years of this study. **Productivity:** no significant variations in plant abundance. The crop energy output (indicator considered for the provisioning ecosystem services) was not significantly different for the wheat culture with or without BC addition. **Other effects:** no changes in soil greenhouse gas emissions nor in the trade-offs with other ecosystem services. Soil pH after BC application: 8.2–8.3.	Francioni et al., 2022
7	Gussone Park of the Royal Palace of Portici, Italy	**1.** Beech wood (*Fagus sylvatica*) *T* = 550 °C Slow pyrolysis pH = 9.28 **2.** 30 t ha^{-1} **3.** *Solanum melongena*, *Foeniculum vulgare*, *Lactuca sativa*, *Allium cepa*, *Cucurbita pepo*, and *Lycopersicon esculentum*	**1.** Andisol (WRB) **2.**Texture: loam pH = 8.02 OC content = 22.13 g kg^{-1}	2 years	**Soil carbon**: significantly higher OC content. **Productivity:** yield was significantly affected by crop type and the interaction between crop type and experimental year. In general, BC showed a growth-promoting effect in the first year, ranging from 12% in tomato to 37% in Aubergine, compared to the control. However, the positive effect of BC persisted only in Aubergine and Lettuce, while it proved negative in the other crops, reaching 44% in Rape. Growth of plants treated with biochar alone was mainly affected by soil pH, NH_4, and OC content in the first year, while total nitrogen content was the main factor affecting growth in the second year. **Other effects**: soil pH decreased significantly after the second year in all treatments (no BC effect).	Iacomino et al., 2022
8	Gorizia, Italy	**1.** Holm oak wood *T* = 650 °C Slow pyrolysis Residence time = 12–18 h, pH = 9.3 **2.** 10.9 t C ha^{-1} (ca. 20–40 t ha^{-1}) **3.** *Vitis vinifera*	**1.** Classification non provided **2.** Texture: clay loam, silty loam pH = 8.00–8.10 OC content = 1.1–2.1%	3 years	**Soil Carbon:** increase in TOC (around a 13% in average). **Productivity:** BC did not affect grape yield and must quality. **Other effects:** BC significantly increased soil water content with respect to the control in site S2 (from 18.9% to 19.5%). BC caused a slight but not significant reduction in cumulative N_2O emissions, alone and together with inorganic fertilizer or compost. Soil bulk density was lower in BC treated soils. Soil pH after BC application: no data.	Sánchez-Monedero et al., 2019
9	Parma, Italy	**1.** Wheat bran pellets. (**B1**) *T* = 800 °C Slow pyrolysis pH = 8.2 (**B2**) *T* = 1200 °C Fast pyrolysis pH = 11.20 **2.** 14 t ha^{-1} **3.** *Lycopersicon esculentum*	**1.** Classification non provided **2.** Texture: silty clay textured pH = 8.1 OC content = 22.50 g kg^{-1}	3 months	**Soil carbon**: significant increase of soil C in both BC treatments compared to control at the end of the experiment: 2.84% for **B1** treatment and 3.19% for **B2** treatment, compared to 2.47% for control. The net gain in soil C was less than the amount of C applied together with BC amendment. **Productivity:** not enhance in tomato yield. No changes in tomato quality; stimulated plant growth and N, P and base cation contents at harvest, by the reduction of the leaf water potential in the warmer period. Results showed that BC amendment may ensure the same yield while using less external input such as fertilizers and irrigation water. **Other effects:** an overall amelioration of soil quality and fertility. Significant increase of the soil cation exchange capacity and the availability of macronutrients. Soil pH after BC application: 8.5–8.9.	Vaccari et al., 2015
10	Prato Sesia, Italy	**1.** Maize pelletized silage T = 1200 °C Residence time = 40 min pH = 11.6 **2.** 30 t ha^{-1} **3.** *Populus Canadensis*	**1.** Entisol (USDA) **2.**Texture: sandy loam pH = 5.4 OC content = 1.4%	8 months and 3 years	**Soil carbon**: BC showed low decomposition rates and a protection effect on original SOM after 8 months. There is a root-induced priming effect on biochar decomposition. Decreased decomposition of SOM by 16% in absence of roots (negative priming effect) over the	Ventura et al., 2015; Ventura et al., 2019; Pulcher et al., 2022

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Table 2 (*continued*)

	Location	1.Biochar feedstock, pyrolysis temperature and pH 2.Application rate 3.Target crop	1. Soil classification 2. Soil characteristics	Time span of the study	Impact of BC application*	References
					3 years period and increased soil C stock in the long term. Confirmed positive effect of roots on biochar decomposition. **Productivity:** no data. **Other effects:** significant increase in soil water content. Soil pH after BC application: no data.	
11	Cadriano, Italy	**1.** Mixed feedstock of fruit trees pruning wood T = 500 °C pH = 9.8 **2.** 10 t ha^{-1} **3.** *Malus domestica*	**1.** Classification non provided **2.**Texture: clay loam pH = 6.6 SOM = 1.06%	16 months	**Soil carbon**: no data **Productivity:** fruit production in the orchard was on average 17.3 kg tree^{-1}, and no differences were observed between yield of treated and untreated plants. Soil-applied biochar did not affect leaf Chl content and leaf dry weight. **Other effects:** cumulative NO_3^- leaching was not affected by BC after 4 months, whereas in the following year it was significantly reduced by 75% over the control. BC treatment did not significantly affect microbial biomass N, which was only slightly lower in the presence of biochar. Soil pH after BC application: no data.	Ventura et al., 2012
12	Mirandela, Portugal	**1.***Acacia dealbata* wood pH = 8.0 **2.** 5 t ha^{-1} **3.** *Olea europaea*	**1.** Classification non provided **2.** Texture: loamy sand pH = 5.8 OC content = 7.82 g kg^{-1}	4 years	**Soil carbon**: significantly higher levels of organic C (data no shown). **Productivity:** olive yield was not significantly different. **Other effects:** increased Cation Exchange Capacity. Soil pH after BC application: no data.	Lopes et al., 2022
13	Mirandela Portugal	**1.** Not specified (commercial) **2.** 10 t ha^{-1} + conventional fertilization **3.** *Olea europaea* L.	**1.** Leptosol (WRB) **2.**Texture: sandy loam pH = 5.1 OC content = 4.4 g kg^{-1}	2 years	**Soil carbon:** no data. **Productivity:** no significant effect on crop yield. Enhanced concentrations of polyphenols with high nutritional value (average annual increase of 25.6%, 84.8% and 11.6% for 3.4-dihydroxyphenylglycol, oleuropein and rutin, respectively). **Other effects:** no data. Soil pH after BC application: no data.	Martins et al., 2022
14	Poulão, Bragança, Portugal	**1.** Silver wattle (*Acacia dealbata*) pH ≤ 9 **2.** a 10 t ha^{-1} + P fertilization **2.** b 10 t ha^{-1} + N fertilization **3.** 4 years *Zea mais* (summer culture) and *Avena sativa*, (winter culture)	**1.***Eutric Fluvisol* (WRB) **2.** Texture: sandy clay loam pH (HO_2) = 5.54 pH (KCl) = 4.64 OC content = 12.71 g kg^{-1}	2 years	**Soil carbon**: Increased total organic C in soil (incineration), not significant increase in easily oxidizable C in soil (wet digestion, Walkley-Black), quantitative data not available. **Productivity:** not increase in the productivity in comparison with the untreated control (Arrobas et al., 2022). Reduced maize dry matter (DM) yield by 15.6% in comparison to the untreated control, indicating N immobilization by biochar at low N rates (N0 and N50) (Rodrigues et al., 2021). **Other effects:** Increased, pH, CEC, and extractable P and greatly reduced soil available N. Soil pH after BC application: ~ 6.3.	Rodrigues et al., 2021; Arrobas et al., 2022
15	Alcalá, de Henares Spain	**1.***Pinus pinaster* **(B1)** fully pyrolyzed pH = 8.6 **(B2)** medium pyrolyzed pH = 7.9 **2.** 40 t ha^{-1} **3.** *Zea mais*	**1.** Classification non provided **2.** Highly fertile soil pH = 7.9 SOM = 3.5%	1 year	**Soil carbon:** organic matter was not significantly improved. **Productivity: B1** significantly enhanced cob weight, grain weight, and cob production (63.4–84% based on dry grain weight). **B2** had no effect on corn production. **Other effects:** Increased sulphate, magnesium, conductivity, and saturation percentage of soil. Soil pH after BC application: 8.0.	Aguirre et al., 2021
16	Coria del Rio, Spain	**1.** Olive mill pomace. T = 500 °C Slow pyrolysis Continues process for 15 min, pH = 9.9 **2.** 6.67 t ha^{-1} **3.** *Olea europaea L.*	**1.***Xerochrept* (USDA) **2.**Texture: sandy loam pH = 7.6 OC content = 1.2%	~1 year	**Soil carbon:** no data **Productivity:** around 15% increase in the net fruit weight but not significant differences in oil production. BC caused a greater accumulation of water at the fruit. **Other effects:** decreased soil penetration resistance and increased soil moisture. Soil pH after BC application: 9.4.	De la Rosa et al., 2022
17	Caldes de Montbui, Spain	**1.** Pine chip T = 600–900 °C Holding time = 10s pH = 11.5 pH = 11.1 **2. a.** 12 and 50 t ha^{-1} + pig slurry	**1.***Fluventic haploxerept* (USDA) **2.**Texture: sandy loam pH = 8.2	30 monthsand 6 years	**Soil carbon**: C sequestration increased with BC rate (23 and 68% higher than in the control for the 12 and 50 t ha^{-1} treatments, respectively). **Productivity:** no significant effects on barely crop parameters. **Other effects:** no differences in CEC and pH, no	Marks et al., 2016; Llovet et al., 2021

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Table 2 (*continued*)

	Location	1.Biochar feedstock, pyrolysis temperature and pH 2.Application rate 3.Target crop	1. Soil classification 2. Soil characteristics	Time span of the study	Impact of BC application*	References
		2. b. Fresh and aged biochar. 12 and 50 t ha^{-1} + pig slurry **3.** *Hordeum vulgare*	OC content = 0.74% Carbonates = 11%		significant effects on crop parameters, interference in the N cycle; increases in availability of K and S. BC ageing (6 years) provoked a loss of nitrate mitigation potential, and indeed ammonium production was stimulated at the 50 t ha^{-1} rate. The 50 t ha^{-1} treatment also adversely affected nematode and collembolan functional diversity. Moisture levels were significantly enhanced at two sampling dates (5th April and 5th July) in fresh BC treated soils, and the effect was more pronounced with 50 t ha^{-1} rate. Soil pH after BC application: no changes.	
18	Arganda del Rey, Spain	**1.** Holm oak chips T = 600 °C Slow pyrolysis pH = 10.06 **2.** 20 t ha^{-1} year^{-1} (5 years) **3.** *Hordeum vulgare, Helianthus annuus, Triticum aestivum,* and *Camelina sativa*	**1.***Xerofluvent* (USDA) **2.** Texture: loam pH = 8.8 OC content = 10.0 g kg^{-1}	6 years	**Soil carbon**: OC content increased significantly (to around 30 g kg^{-1}); SOC mineralization, estimated as basal respiration, significantly increased (it was approximately 10 μg CO_2-C g^{-1} day^{-1} in unamended condition and 18 CO_2-C g^{-1} day^{-1} with BC). The ratio of evolved CO_2-C to soil TOC (mineralization quotient) decreased significantly with BC application. The results suggest that biochar is an effective amendment for C sequestration in soil. **Productivity:** no data. **Other effects:** Shannon diversity index of the bacterial community was significantly increased. Soil pH after BC application: no changes.	Moreno et al., 2022
19	Santa Cruz, Spain	**1.** Olive tree pruning T = 450 °C Slow pyrolysis pH = 9.45 **2.** 40 t ha^{-1} **3.** *Triticum aestivum*	**1.***Vertic Calcixerert* (USDA) **2.** Texture: clay pH = 8.2 OC content = 8.26 g kg^{-1}	1 year	**Soil carbon**: increased contents of organic C (by 57%) but no significant changes in soil dissolved OC. **Productivity:** significant increases in the biomass of the stem, spike and in the aboveground plant biomass 124 and 184 days after sowing. Aboveground biomass, control 1.115 g m^{-2}, biochar 1.354 g m^{-2}. Grain production was negatively correlated with soil compaction and positively correlated with soil moisture. However, the data obtained at harvest did not show any significant effect of BC addition on grain yield. With respect to grain quality and nutrient content, only the Fe and Zn concentrations were slightly lower for the BC treatment. **Other effects:** decreased soil compaction. Increased soil water-retention capacity (increase in the range 8% - 40%), macronutrients (total N and available P, K and Mg) and micronutrients (available Cu and Zn); not significant changes in pH, contents of available Fe and Mn, labile C and N forms and ammonium, nitrate or microbial biomass. Soil pH after BC application: no changes.	Olmo et al., 2014
20	Coria del Rio, Spain	**1. (B1)** Pine wood *T* = 620 °C, pH = 10.4 **(B2)** Paper sludge T = 500 °C pH = 10.4 **(B3)** Sewage sludge, *T* = 600 °C pH = 6.7 **(B4)** Grapevine wood, T = 500–620 °C pH = 10.3 **(B1) (B2)**, **(B3)**, Fast pyrolysis. 20 min at maximum temperatures. **(B4),** kiln method **2.** 15 t ha^{-1}, 1.5 t ha^{-1}	**1.** Calcic Cambisol (WRB) **2.**Texture: sandy loam pH = 8.5 OC content = 10 g kg^{-1}	3–4 months	**Soil carbon:** no data **Productivity:** no significant increase of the total biomass production excepting with **B4**, at the dose of 15 t ha^{-1}. The BC with the lowest capacity of water retention. **Other effects:** BC amendment at dose of 15 t ha^{-1} caused a relative increase of WHC up to 7% with **B2**. Soil pH after BC application: 8.3.	Paneque et al., 2016
21	Vimbodì-Poblet, Spain	**(B1)** Pine wood remains T = 600–900C pH = 11.5 **(B2)** Corn cobs remains *T* = 450–500C, Slow pyrolysis, pH = 10.3	**1.***Fluventic Haploxerept* (USDA) **2.**Texture: sandy loam	26 months	**Soil carbon**: significant increases in total OC (60% as average value after 26 months) and in stable OC content. The inorganic C content was very low, and no significant differences were found between treatments. Resistant organic carbon, estimated as non-hydrolysable organic	Raya-Moreno et al., 2017; Andrés et al., 2019

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Table 2 (*continued*)

	Location	1.Biochar feedstock, pyrolysis temperature and pH 2.Application rate 3.Target crop	1. Soil classification 2. Soil characteristics	Time span of the study	Impact of BC application*	References
		Residence time = 2 h **2.** 5 t C ha^{-1} (6.5 g Kg^{-1}) **3.** *Vitis vinifera*	pH = 7.2 OC content = 0.97%		carbon and as non-oxidizable, led to similar values in control soil and treatments. No change in BC organic carbon in soil. **Productivity:** no data. **Other effects:** no changes in the functional microbial diversity, the microbial abundance nor the biodiversity of soil micro-arthropods. Reduced soil microbial biomass. Soil pH after BC application: 7.7.	
22	Jumilla, Spain	**1.** Holm oak wood T = 650 °C Slow pyrolysis Residence time = 12–18 h pH = 9.26 **2.** 20 t ha^{-1} 2013 + 20 t ha^{-1} 2015 **3.** *Olea europaea L.*	**1.** Haplic Calcisol (WRB) **2.**Texture: sandy loam pH = 8.01 OC content = 1.68%	3 years	**Soil carbon**: higher TOC (around 3%). No differences in Dissolved organic carbon after 2 years. Increase in TOC (2.95%). No changes in extractable OC content after 3 years **Productivity:** any significant impact on the nutritional (N and macro and micro-nutrients) status of the olive trees after 2 and 3 years. Any significant impact on the production of olives after 3 years there was a trend towards an increase in production. **Other effects:** no significant effects on soil WFPS (water-filled pore space) and water content. Soil pH after BC application: no data.	Sanchez-Garcia et al., 2016; Sánchez-Monedero et al., 2019; FAO and ITPS., 2021
23	Şanlıurfa, Turkey	**1.** Pistachio shells, corn cobs and cotton straws. *T* = 300 °C **2.** 4 and 8 t ha^{-1} + NPK fertilization **3.** *Zea mais*	**1.**Vertic Torrifluvent (USDA) **2.**Texture: clay pH = 8.2 SOM = 1.4%	2 years	**Soil Carbon:** changes in SOM were either insignificant or negative. **Productivity:** insignificant impact on yield **Other effects:** significant increases in average values of soil porosity compared to control. Slightly increases in Available Water Content (AWC). AWC values in the FC65 (water was applied at 65% of field capacity) parcels showed that BC doses of 4 t ha^{-1} and 8 t ha^{-1} had higher AWC values than FC100 control parcels. Increased soil total nitrogen and aggregate stability. Soil pH after BC application: no data.	Bilgili et al., 2019

4.2. *Use of biochar in Mediterranean soil: Case studies*

The effects of biochar on soil fertility and carbon sequestration have been mainly studied in lab-scale trials. In order to understand the real impact of biochar application on soil it is crucial to rely on field observations and, in order to draft conclusions, it is important to gather the results of different long-term field trials covering an expansive spatial heterogeneity (Ventura et al., 2019; Vijay et al., 2021). Biochar characteristics (pH, % C, C/N), application rate, time and pedo-climate conditions are the main factors affecting the impact of biochar application and its stability in soil. This variability makes it difficult to compare results from field studies, and this adds to the discussion about the effects of biochar (Vijay et al., 2021).

As highlighted in the section 4.1, water scarcity and continuous loss of organic carbon are among the mean threats affecting Mediterranean soil. Biochar application to soil can improve water retention due to its high surface area and the presence of micropores. If correctly managed, biochar amendment can be a valuable technique for enhancing the

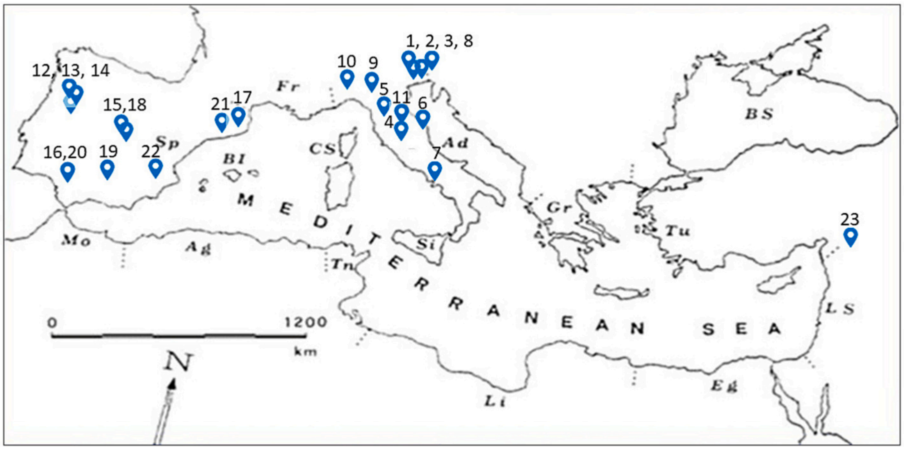

Fig. 1. Location of the biochar field trials carried out in the Mediterranean region. Each field study was identified with a number corresponding to the literature reference indicated in Table 2. The geographical map has been modified from Gómez Garreta et al. (2001).

capacity of agricultural systems to buffer the degradation of the Mediterranean soils and to sequester carbon (Vaccari et al., 2011).

To our knowledge, the Mediterranean field trials testing biochar as amendment have been carried out mostly in the North-Western part of the Mediterranean basin, i.e., in Italy, Spain and Portugal (Fig. 1) with only one study in the Eastern part (Turkey, Bilgili et al., 2019).

In Table 2, a summary of the results from these studies is reported, along with the biochar and soil characteristics of each field study. The bibliographic review on field trials has been performed using the online databases Scopus and Google Scholar. Peer reviewed publications were searched by using the following search tips: "field trial" AND "biochar" AND "Mediterranean" in the abstract, title and keywords. Moreover, the number of papers was reduced to 36 by applying the following criteria:

1. Mediterranean basis as geographical area
2. Field studies including crop cultivation
3. Field studies including data about soil carbon and/or plant growth/ yield
4. Experimental studies not dealing with polluted soils

We also included other studies that fulfil these points but did not appear in our online search.

Field observations in the Mediterranean basin showed effects of the biochar application mainly on carbon dynamic; microbial community; oil WHC; pH and nutrient content, and crop yield.

4.2.1. Carbon dynamics

Biochar addition led in general to an increase of TOC (in the range of 8% 200%) (Ameloot et al., 2014; Giagnoni et al., 2019; Francioni et al., 2022; Iacomino et al., 2022; Lopes et al., 2022; Sánchez-Monedero et al., 2019; Moreno et al., 2022; Olmo et al., 2014; Raya-Moreno et al., 2017; Vaccari et al., 2015; Rodrigues et al., 2021;). In this regard, Ventura et al. (2019) observed a decrease of SOM decomposition rate (e.g., negative priming effect) in a three year field study in Northern Italy. This negative priming effect may be due to the porous biochar structure that can increase the stability of soil organic carbon against biodegradation as explained in the section 3.1.

The highest organic carbon content increase after biochar addition has been reported in field studies with biochar application rates higher than 40 t ha^{-1}. Moreno et al. (2022) reported an increase in TOC of 10-30 g Kg^{-1} after an application of 100 t ha^{-1} (20 t ha^{-1} year^{-1}). Francioni et al. (2022) reported that TOC doubled after two years of application of 60 t ha^{-1} of biochar. Sánchez-García et al. (2016) and Sánchez-Monedero et al. (2019) reported an increase of about 80% in TOC after two and three years, respectively, of applying a total of 40 t ha^{-1} of biochar.

However, neutral or negative changes in TOC after biochar amendment have also been reported (Aguirre et al., 2021; Ameloot et al., 2014; Bilgili et al., 2019; Rutigliano et al., 2014). Aguirre et al. (2021) found increases in soil TOC with the addition of biochar, but these differences were not significant. Ameloot et al. (2014) suggested that, at Beano and Rocca Bernarda sites, TOC did not increase in biochar treated soils due to the degradation of labile biochar components taking place over a longer period (four and two years, respectively), compared to the Rivignano site where an increase in TOC was observed after seven months of treatment. Tillage-induced movement of biochar and a lower application rate could have influenced soil organic carbon content at the Beano site. Rutigliano et al. (2014), however, reported that biochar application in the form of particle size (<1 cm) did not significantly contribute to the organic carbon pool present in the analyzed fine earth (<2 mm). They suggested that a longer time is necessary for biochar to be fragmented into smaller particles (<2 mm) because of physical, chemical and biological degradation.

Finally, Bilgili et al., 2019, stated that the observed decrease in SOM could be due to stimulated microbial activity with the application of biochar (positive priming effect). Noticeably all studies that were reporting no biochar effects on SOM used low-temperature biochar (350–500 °C), which presumably has negatively affected the protective role of biochar on SOM.

4.2.2. Microbial communities

Rutigliano et al. (2014) found a significant increase in microbial activity during the first three months after biochar addition but no effect after 14 months, highlighting a decrease of the biochar role with time. The same authors stated that soil pH could have contributed to this effect, as the soil's pH acidity (5.23) increased in the first three months to 6.7 favouring microbial activity and decreased again after 14 months to 5.3.

Therefore, while biochar incorporation into the soil shows its potential to achieve carbon sequestration, in long-term studies (six to seven years), the biochar addition has led to variations in the biochemical activities of soil, stimulating different metabolic pathways compared to non-amended soil, and changes in the composition and diversity of soil bacterial community (Moreno et al., 2022). Indeed, the soil microbial activity seems to have shifted from the use of labile plant-derived sugars towards the use of more recalcitrant carbon compounds (Giagnoni et al., 2019). This effect has been interpreted as a response to the changes observed in carbon forms, inorganic nitrogen forms and phosphorus availability (Giagnoni et al., 2019; Moreno et al., 2022). Conversely, in short and mid-term field trials (three to five years), the biochar treatments showed minimal impact on microbial parameters such as; biomass and respiration; abundance; diversity, and composition (Ameloot et al., 2014; Andrés et al., 2019; Baronti et al., 2014; Castaldi et al., 2011; Marks et al., 2016; Olmo et al., 2014).

4.2.3. Soil water holding capacity and plant productivity

A general agreement has been established on the effect of biochar on soil-water relations. In fact, several studies here considered reported an increase of the soil holding capacity after biochar addition (Aguirre et al., 2021; Baronti et al., 2014; Bilgili et al., 2019; De la Rosa et al., 2022; Llovet et al., 2021; Olmo et al., 2014; Paneque et al., 2016; Ventura et al., 2015), leading to a lower nutrient leaching and a higher plant available water content.

Especially in Mediterranean soils, where water availability is a limiting factor, the effect of biochar on water dynamics is a determinant for the observed crop yield improvement. Nevertheless, among all the studies reporting improved soil water content, only five reported enhanced plant growth and/or yield, likely related to the increase of soil WHC (Aguirre et al., 2021; Baronti et al., 2014; De la Rosa et al., 2022; Olmo et al., 2014; Vaccari et al., 2015). In this regard, Olmo et al. (2014) found a positive correlation between wheat grain production (g m^{-2}) and soil moisture. The biochar treated plots showed the highest soil moisture during the experiment, at 8%–40% higher than the control plots. Also, De la Rosa et al. (2022) found an increased plant yield (an 18% increase in Kg of olives per tree) in biochar treated soils, with olives from trees grown on biochar treated soils accumulating more water than olives from control trees.

After two years of biochar application, also Baronti et al. (2014) observed increases in available soil water content (3.2%–45% in the 16.5–33 t ha^{-1} application rates, respectively) and in leaf water potential (24–37%) during droughts. Moreover, an increase of grape yield per plant in biochar treated plots (increase ranged from 16%–66%) was highlighted by Genesio et al. (2015), harvesting during the four years after the first biochar addition into the soil. The effect of biochar on yield was found to be higher in the years with the lowest rainfall, suggesting a protective effect of biochar against plant water stress (Genesio et al., 2015). Also, Vaccari et al. (2015) showed an effect of biochar on plant-water relations as it was observed that the use of biochar led to a substantial increase of the amount of tomato plant biomass produced per unit of irrigation water applied. This effect, together with the higher soil nutrient contents (nitrogen and phosphorus), led to higher plant growth, but not higher tomato yield. Ventura et al. (2015) confirmed the positive effect of biochar in enhancing soil water content during summer.

Finally, Aguirre et al. (2021) found an increase of 63.4–84% in the dry grain weight of maize in fully pyrolyzed biochar treated soils that also presented a higher water saturation percentage (33.64%) and Magnesium content (14.5 mg L^{-1}) than control soils (29.9–9.5 mg L^{-1}, respectively).

On the contrary, several authors (Bilgili et al., 2019; Llovet et al., 2021; Sánchez-Monedero et al., 2019) observed negligible impact of biochar application on maize, grape yield, and barley growth, respectively, though soil available water content increased in biochar treated soils. It is interesting to note that Bilgili et al. (2019) observed that the available water content increased slightly in all biochar applied parcels and this increase was statistically significant only in the parcels with limited irrigation, showing the potential of biochar in water storage for plant during critical periods. Paneque et al. (2016) did not find any difference in sunflower biomass production in the plots treated with a biochar from paper sludge that have caused an increase of up to 7% in soil WHC. Interestingly, in the same study, authors showed plant biomass enhancement in soils treated with a grapevine wood derived biochar applied at a rate of 15 t ha^{-1}. They linked the enhancement of plant biomass production with the lower specific surface area (SSA) of biochar. A high SSA of biochar promotes adhesion and cohesion between biochar and water (Dempster et al., 2012) and can promote competition for water between plants and biochar under water-limiting conditions, such as the summer periods in the Mediterranean regions. In this regard, Sánchez-García et al. (2019)) showed that, although with increasing temperatures of pyrolysis the porosity of biochar increases, whereas its hydrophobicity decreases, the tortuosity of the pores could not guarantee the availability of water to plants. In fact, they suggested 400 °C as the optimal temperature of pyrolysis for tree pruning derived biochars to avoid negative effects from a hydrological point of view. It is interesting to notice that, from the considered studies in this review, the ones that have shown an increase in crop yield, as a result of soil water content enhancement in biochar treated soils, have used biochars pyrolyzed at low temperatures from 450 °C–500 °C (data of Aguirre et al., 2021 is not available). Unfortunately, other studies have not reported values of soil WHC and therefore a deeper comparison among studies is not possible. The effects of biochar in soil water content depend also on the soil type and on biochar application rates and, thus, it is difficult to find a direct relationship among the temperature of pyrolysis, feedstock type and soil water content and/or crop yield (Sánchez-García et al., 2019).

4.2.4. *Other soil characteristics (pH, nutrient content) and plant productivity*

Other studies considered have reported higher growth and/or yield in biochar treated soils (Iacomino et al., 2022; Vaccari et al., 2011; Vaccari et al., 2015) and related these effects to soil properties other than WHC. In these cases, growth and/or yield increases have been ascribed to the pH changes in soil that affects nutrient availability, the mulching effect of biochar increasing soil temperature in winter crops and less weed competition as biochar reduced weed biomass (Vaccari et al., 2011). Iacomino et al. (2022) reported modification of plant yield in biochar treated soils, depending on the plant species and on the time from biochar application. In this study, the growth of plants treated with biochar alone was mainly affected by soil pH, NH_4, and organic carbon content in the first year, while total nitrogen content was the main factor limiting growth in the second year. Similarly, Rodrigues et al. (2021) found reduced maize dry matter yield by 15.6% in biochar treated soils, as a result of N immobilization by biochar when low N rates were applied into the soil (0-50 kg ha^{-1} of N). On the contrary, Vaccari et al. (2015) found that the above and below ground growth of the tomato plants was stimulated by biochar under fertile conditions. Likely, the effect of biochar on plants depends on soil nutrient concentration, in presence of nitrogen or phosphorus shortage, biochar, adsorbing the nutrients, competes with plants for their availability. Conversely, where nutrients are not a limiting factor, biochar enhances soil fertility and reduces nutrient leaching.

No changes or negative effects in crop productivity have been reported for the *Vitis vinifera* grape (Sánchez-Monedero et al., 2019); *Olea europaea* olive (Lopes et al., 2022; Martins et al., 2022); *Zea mais* cob (Arrobas et al., 2022; Bilgili et al., 2019; Rodrigues et al., 2021); *Triticum aestivum* wheat (Francioni et al., 2022), *Hordeum vulgare* ear (Marks et al., 2016), and the *Malus domestica* apple (Ventura et al., 2012). The different responses in the crop yield observed after biochar amendment may be related to the initial soil pH. In fact, most of the field studies where no effect on crop yield was reported were carried out on soils with a pH $\geq$ 8. Conversely, studies where positive effects on crop growth or yield have been reported after biochar application have generally lower soil pH (Aguirre et al., 2021; Baronti et al., 2014; Bilgili et al., 2019; De la Rosa et al., 2022; Francioni et al., 2022; Marks et al., 2016; Sánchez-Monedero et al., 2019; Vaccari et al., 2011). Indeed, biochar, which generally has basic pH, when added to acidic substrates has a higher activity in modifying soil properties with respect to alkaline soil conditions.

5. The “biochar latium” research project

Within this context, the project titled “Valorization of the biochar produced from the recovery of woody wastes from Lazio supply chains” is a research project funded by Lazio Innova (Lazio Regional Development Agency) within the POR-FESR framework (https://www.biocharlatium.eu/).

The project deals with important issues such as environmental sustainability, green economy, and carbon storing. It aims to test the efficacy of the production of biochar from woody waste generated in the hazelnut and olive local supply chains and its application as soil amendment. For this purpose, the project will assess:

-the effects and the most efficient application mode of biochar (alone or with compost) on nutrient deficient soils,

-the effects, and the most efficient application mode of biochar (alone or with microorganisms) on contaminated soils.

6. Conclusions and perspectives

Biochar application as soil amendment can be an effective strategy for carbon sequestration in view of a carbon farming practice. In this context, biochar is particularly interesting for the Mediterranean environment whose soils are particularly vulnerable to water scarcity and loss of soil organic matter.

In this review, only outcomes from field trials in the Mediterranean region performed in Italy, Spain, Portugal and Turkey were reported. In particular, the effects of biochar on soil carbon cycle, soil WHC and crop productivity can be summarized as follows:

- Biochar has good potential to store carbon in Mediterranean soils as it has a great proportion of recalcitrant carbon.
- The effects of biochar on soil microbial community show different responses. The application of biochar can stimulate microbial activity in the short term. On the contrary, in the medium term, no significant effects on the soil microbial community have been observed. The reasons for these results are not entirely clear, but could result from changes in soil conditions, such as modification of pH.
- Regarding the soil WHC, several studies in the Mediterranean basin have shown that biochar can effectively improve soil water content in adverse water conditions such as during drought and summer.

However, to date, not enough information is available to reach a definitive conclusion on the effects of biochar on the plant-soil system in the Mediterranean basin. In order to compare the different field studies, it is vital that each study reports a relevant set of basic parameters to link biochar effect on soil and plants productivity such as: soil pH, TOC and soil WHC before and after biochar application. It is also important to clearly indicate the main characteristics of the biochar applied to soil: pH, feedstock, temperature of pyrolysis, particle size and elemental composition (H, C, N, O).

On the other hand, considering the good potential of biochar in carbon-farming and the multiple factors affecting its impact on crops, it would be desirable for more long-term field experiments to be performed on various Mediterranean pedo-climatic conditions, in order to draw up guidelines on the use of biochar for a carbon-farming practices, and the optimizing of its effect on crops.

Funding

The project “Biochar Latium” N. CUP J85F21000410002 has been funded by Lazio Region – Lazio Innova (Italy), within POR FESR Lazio 2014–2020 programme.

Declaration of Competing Interest

None.

Data availability

No data was used for the research described in the article.

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