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Review

The Application of Biochar in the EU: Challenges and Opportunities

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Abstract: Biochar application to agricultural soils is an interesting emerging technology with promising potential for long-term carbon storage, sustainable waste disposal, and soil fertility enhancement. Extensive information exists in the literature on the highly beneficial properties of biochar. Nevertheless, systematic application of biochar on European agricultural soils may have wide ranging policy implications as well as environmental and public health concerns. In this paper we critically review existing scientific evidence from a European policy perspective and identify research gaps for future comprehensive assessments of the policy, environmental, economic, and health implications of the systematic use of biochar in European agricultural soils.

Keywords: biochar; soil protection; soil fertility; waste management; climate change; human health

1. Introduction

Charcoal is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Historically, production of wood charcoal in districts where there was an abundance of wood dates back to a very ancient period. It has been widely used as smelting fuel for metallurgical purposes and this has been one of the major causes of deforestation in Europe. Charcoal is the traditional fuel of a blacksmith's forge and other applications where intense heat is required. Only recently did the new term "biochar" emerge to describe exactly the same material [1]. The main difference to charcoal is the purpose of its use: biochar is intended as an amendment to soils for increased soil fertility while at the same time ensuring long-term carbon storage, with beneficial side effects on the global carbon balance as a mitigation tool for global climate change. The scientific basis for such an alternative use of charcoal to the traditional use as fuel has been inspired by the discovery of the carbon-rich soils of the Central Amazon, known as "Terra Preta de Indios". These soils, occupying *ca*. 10% of Amazonia, are characterized by high levels of soil fertility due to carbonaceous residues from slash-and-burn cultivations of nomadic indigenous tribes mixed with other organic residues from the local waste of the moving populations. These dark Amazonian soils were fully described already in 1966 by Wim Sombroek [2] and were "re-discovered" by the modern biochar community in more recent times [3]. Based on the evidence of this ancient traditional knowledge and cultivation techniques a complete new research and stakeholder community has emerged in the last few years [4]. The combination of traditional knowledge, scientific evidence, climate change preoccupations, food security issues, and increasing difficulties in cost effective disposal of organic waste products has generated a very effective "cocktail" of win-win solutions that seem very appealing to businesses and policy makers.

2. The EU Policy Perspective

Biochar is a technology with implications in various EU policy areas, including environment protection, waste management, agricultural policy, climate change policy, development aid, research policy, industry and energy. The big challenge is to integrate the main benefits and impacts into a common framework, finding the most suitable and cost-effective solutions in order to maximize benefits while respecting intra-international laws and regulations. Here, we briefly revised some of the potential benefits related to the development of a biochar strategy in a European policy perspective, also highlighting the main concerns and knowledge gaps, but keeping in mind that, at the moment, there is no coherent EU policy addressing the biochar issue.

It is important to point out that under EU regulations biochar, which is not a primary or co-product of a pyrolysis process, is considered waste and is therefore regulated by the European Directive on Waste (2008/98/EC) [5]. As the majority of biochar is regarded as a by-product of bioenergy production, it is classified as waste and it must comply with waste protocols which blocks, *de facto*, its agronomic utilization. In any case, biochar that could potentially be applied to soil, according to the complex interpretation of EU regulation, must respect the national legislations that are not specifically designed for biochar but adopt threshold limits of potential analogous material (sewage sludge, amendments, *etc*.).

In order to move forward towards a coherent and common policy on biochar, relevant aspects of biochar application are discussed in view of the EU Soil thematic strategy, the EU climate change policy, the EU waste policy and the EU energy policy.

2.1. EU Soil Thematic Strategy

Given that by definition biochar should be considered a soil improver, its use should be viewed from the EU Soil Thematic Strategy (COM (2006) 231final) [6] and the related proposed Soil Framework Directive (COM (2006) 232) [7] perspective. The Thematic Strategy explicitly mentions the constant decline in organic carbon content as one of the major threats to European soil and therefore, the application of biochar could seem a valuable solution to reverse this negative trend. In addition, the strategy singles out the specific soil functions that EU legislation should protect. One of the main functions identified is the role of soil to act as a carbon sink and therefore contribute to climate change mitigation. Biochar is certainly a valid technology for long-term carbon storage in soils and therefore perfectly consistent with these strategy specifications [8]. In addition to this aspect, some co-benefits may result from the use of biochar as a soil amendment. Due to its porous structure and large surface area, biochar applications showed to positively influence soil field capacity, nutrient availability, fertilizer use efficiency, pH ("liming effect"), and cation exchange capacity-CEC [4,9–11]. However, the interaction between the soil and biochar type (in terms of feedstock and process conditions) needs to be further investigated, in particular for certain important issues, such as change in heavy metal availability, pesticides sorption, and introduction of metal contaminants [12]. Some positive indications can be found in the extensive review by Beesley *et al.* [13], who demonstrated clear potential for the reduction of a variety of organic and inorganic contaminants present in soils in their most mobile forms. Moreover, in an experiment testing the use of biochar in contaminated soils, Beesley and Marmiroli [14] reported a marked reduction of Cd and Zn leachate concentrations. Sorption was indicated as the main mechanism of retention for those metals, while no significant decrease in concentration was detected for As. In contrast, as biochar may be produced from a wide range of organic feedstocks, it also contains potentially toxic elements (PTEs) such as Cu, Pb, and As. This raises the issue of how to define concentration limits, for which legislative standards are inexistent at national level for this amendment. Farrell *et al.* [15], for instance, highlighted the difficulties in commonly used PTE extraction methods to assess plant availability of potentially toxic elements in biochar.

Part of this gap is filled by two main voluntary initiatives: The European Biochar Certificate (EBC) [16] and the International Biochar Initiative (IBI). These initiatives are trying to define production criteria and biochar properties and quality, but are not recognized by any national legislation as official methods within EU. In particular, the EBC defines some elemental limits, such as a total organic carbon content >50% and O/C and H/C ratios <0.4 and 0.6, respectively; furthermore, heavy metal thresholds and limits for PAH (<12 mg kg^{-1}), PCB (<0.2 mg kg^{-1}), PCDD, and PCDF (<20 ng kg^{-1}) are provided.

Although biochar contains PAH in relation to the feedstock and pyrolysis process [17], its role as a source or sink (by sorption) of PAH is still debatable [18]. Gomez-Eylez *et al.* [19] conducted an incubation experiment using contaminated soil amended with either biochar or the earthworm *Eisenia fetida* or both. The authors showed that biochar reduces total and bioavailable PAHs, PAH concentrations in *E. fetida* (up to 45%) but also earthworm weight. Loss of earthworm weight in biochar treatments compared to those in the control was also found by Li *et al.* [20]. They also concluded that the presence of toxic compounds was not a likely reason for earthworm avoidance of treated plots, but rather insufficient moisture control. The study of Zhang *et al.* [21] clearly suggested that biochar application enhanced soil sorption of hydrophobic organic compounds, such as phenanthrene, but with varying magnitudes depending on biochar pyrolysis conditions, original soil organic carbon levels, and the contact time between soil and biochar. Quillian *et al.* [18] found an inhibition of PAH catabolism by biochar amendment, most likely ascribed to increased sorption and subsequent reduced bioavailability to soil microbial communities. Moreover, this sorption biochar capacity raises a fundamental issue about the long-term accumulation of PAH in soil. Short-term experiments do not seem to highlight increased PAH bio-availability; however, studies of the dynamics between sorbent saturation and microbial activity in a more long-term perspective are mandatory before large-scale application strategies. Due to its high sorption capacity, biochar can also interfere with the mobility and degradation of herbicides. Some benefits may result for foliar applied pesticides that could be less subject to water contamination [22]. On the other hand, biochar may decrease the efficacy of soil-applied pesticides, leading to higher application rates of certain herbicides in order to obtain the desired level of weed control [23]. Other studies showed that biochar incorporation in soil can have opposing effects on the leaching of pesticides depending on the adsorption strength of the substance [24].

2.1.1. Biochar as Long-Term Carbon Storage for Climate Change Mitigation

Biochar is a form of relatively stable carbon that can effectively act as long term carbon storage and therefore substantially contribute to climate change mitigation strategies. As other Carbon Capture and Storage (CCS) technologies, it allows long-term carbon storage preventing further emissions of CO_2 in the atmosphere. Woolf *et al.* [25] estimated a removal of 0.49 Gt C yr^{-1} from the atmosphere by biochar application that, under a realistic scenario, would require the conversion of 2.2 Gt of C feedstock into biochar every year. Stavi [26] calculated a global sequestration between 2 and 109.2 Pg biochar-C in 1.75 billion ha of degraded and deforested lands and agroforestry systems.

In that context, the alternative use of biomass in combination with waste disposal strategies and technologies may allow long-term storage of organic carbon that would have otherwise been either incinerated or mineralized through composting. Therefore, it may be a valid alternative to other waste disposal technologies [27].

However, one of the main constraints of biochar utilization as an amendment is its variable composition, strongly dependent on the type of feedstock and production process [28]. Schimmelpfenning and Glaser [29], in fact, stressed the need for analytical guidelines for a more strict definition of "biochar", which could guarantee a product with desirable properties for soil amendment and C sequestration without threatening soil health.

Compared to the recommended practices for C sequestration based on improved farm management (e.g., tillage, rotation, land use change, *etc*.), the biochar strategy has several advantages [30]:

(1) the amount of C sequestered is more predictable, due to the recalcitrance of this material. Kuzyakov *et al*. [31] estimated a mean residence time of 2000 years, using ^{14}C labeling incubation;
(2) farmers are not obliged to maintain a management practice (for example no-tillage) for a long period, thus they are more open to market changes;
(3) the sequestration effect is immediate and the rate very high. Cross and Sohi [32] estimated a very small fraction of labile C in biochar and no priming effect on native soil organic matter.

Conversely, the feasibility of biochar application relies on its availability, which depends on the construction of production plants. Studies on pilot projects carried out in Australia [33] have already demonstrated the financial viability of land-based production systems, despite significant technical harvesting and processing hurdles that need to be overcome.

According to Roberts *et al.* [34], the greatest potential for economic profitability of a pyrolysis-biochar system is very high for biomass sources that have a need for waste management, such as yard waste. However, as pointed out by the authors, the transportation distances for feedstock may significantly reduce the economic profitability of those systems; therefore, the unit price for a C credit in a carbon market may be a very sensitive factor toward a widespread diffusion of a biochar strategy.

In that context, the EU Emission Trading System (ETS) legislation allows participants to use most categories of credits from the Kyoto Protocol's Clean Development Mechanism (CDM) and Joint Implementation (JI) mechanism towards fulfilling part of their EU ETS obligations. So far, however, biochar has not been included in the CDM mechanism and the EU ETS, which together account for approximately 97% of carbon trading worldwide [35].

Lacking a clear regulatory framework for biochar, there seem to be important legal aspects that remain to be clarified before the systematic implementation of a biochar market can be envisaged. Clear definition of quality standards, soil permanence, leakage as well as a full assessment of the related risks for long-term application of biochar to agricultural soils, especially in relation to human health and soil biodiversity, will need to be completed before any regulatory framework concerning biochar can be developed. A targeted research agenda addressing policy-relevant questions in relation to biochar could pave the way towards the generalized use of biochar technology in a strictly regulated framework, such as within the European Union.

2.2. Waste Policy

Approximately 120 to 140 million tons of bio-waste are produced every year in the EU (COM(2010) 235). This corresponds to approximately 300 kg of bio-waste produced per EU citizen per year (EC 2011) [36].

The definition of bio-waste is provided by the Waste Framework Directive (WFD) (Directive 2008/98/EC): "Bio-waste includes garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises as well as comparable waste from food processing plants. It does not cover forestry or agricultural residue." Bio-waste should not be confused with the broader category of "biodegradable waste". Biodegradable waste, as defined by the Landfill Directive (Directive 1999/31/EC), includes "any waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, and paper and paperboard."

Throughout Europe, *ca.* 40% of bio-waste is still landfilled (up to 100% in some Member States) (COM(2010) 235). This is not in line with the guiding principles of EU waste and sustainable resource management policy, notably the "waste hierarchy" that should underlie all national waste policies. According to the waste hierarchy as defined in article 4(1) of the WFD, waste prevention is the preferable option, followed by preparing for re-use, recycling and other recovery (e.g., energy recovery). Disposal (e.g., landfilling) is seen as the least desirable option.

However, article 4(2) of the WFD states: "When applying the waste hierarchy referred to in paragraph 1, Member States shall take measures to encourage the options that deliver the best overall environmental outcome. Member States may depart from this hierarchy for specific waste streams, if this is justified by life cycle thinking on the overall environmental impacts of the different waste management options."

Waste streams with high organic carbon content are potentially a feedstock for pyrolysis plants producing biochar [37]. As an alternative to composting, there is a potential for biochar to overcome some of the limitations of composting, such as reduced CO_2 and other gas emissions, stabilization of the output material, facilitated handling, shipping, and distribution. The fully sterile material also eliminates the threat of biohazards. The pyrolysis process, in contrast, depending on the type of feedstock and pyrolysis conditions, may generate chemical hazards to human health, e.g., PAH and others, that need to be carefully screened [18]. In any case, biochar is an appealing technology for the waste industry, given the possibility of large scale installations and the related economies of scale that can be generated compared to traditional composting and disposal of bio-waste. It also has clear advantages to incineration, given the other benefits of biochar as soil improver and carbon storage. In the EU, between 118 and 138 million tons of bio-waste are produced every year, *ca.* 88 million tons of which is municipal waste. This amount is projected to increase, on average, by 10% by 2020 (European Commission, 2010). Transforming this large mass of biomass into stable biochar would clearly be very appealing, given the well documented positive fall-outs of such a waste disposal technology: climate change mitigation, increased soil fertility, improved soil carbon levels, *etc*.

Biochar can be produced from feedstocks with high initial nutrient content, including those not classified as bio-waste such as dairy bedding and manure, to produce a hybrid fertilizer/biochar [11,38]. This process could be an interesting solution to reducing the organic nitrogen load in Europe, fulfilling the limits imposed by the EU Nitrates Directive (1991). In that context, chemical and bioassay characterization of nitrogen availability in biochar produced from dairy manure and biosolids have been explored [39]. Since higher pyrolysis temperature generally reduces nitrogen availability, these types of characterizations are fundamental for designing the best combination (biochar/biosolid/pyrolysis) that could maintain its fertilization power. The risk is to lose the fertilization properties of biosolids and consequently increase the mineral fertilization, if appropriate knowledge and standards are lacking. Other recent research [40] suggested that high-ash biochars with high P concentrations are potential P sources with high-agronomic efficiency. This will help to create agricultural systems with a more closed cycle, avoiding the massive use of external input, especially coming from limited sources (e.g., as for phosphorous).

Very recently, the idea of improving compost quality with biochar has been leading to an increased number of experiments about this issue. Biochar composting with farmyard manure increased the CEC of biochar but also altered its surface properties [41]. In particular, the chars absorbed organic matter and nutrients but the composting process decreased biochar surface area due to the clogging of micropores by sorbed compost-derived materials. Furthermore, biochar composting with poultry manure induced a faster decomposition of poultry manure compared to the control treatment, but it reduced total N losses up to 52% [42].

2.3. Energy Policy

Integration of biochar in heat and renewable-energy production is an opportunity to be explored. Currently, there is no reference to biochar in any of the existing EU legislations related to energy apart from the fact that, as resulting material of an energy process (e.g., pyrolysis, gasification), it is treated as a waste (Paragraph 2). Plants producing biochar are generally broadly classified in pyrolysis and gasification systems: in the former the biomass is heated in the absence of oxygen while, in the latter, biomass is partially oxidized at high temperatures (>800 °C). However, both processes produce noncondensable gases (syngas), condensable vapors/liquids (bio-oil, tar) and solids (char, ash) [43]. Depending on the feedstock and process, syngas is a variable mixture of CO and CO_2, H, CH_4, and N_2, which, if upgraded, can be used in combustive engines to generate electricity. From this perspective, biochar is only a co-product of an energy-supply chain that primarily generates energy. The associated risk of depleting SOC exporting biomass (and hence C), rather than incorporated or returned to the field, may be offset by the same biochar application. In that case, even if C yield of biochar is lower than the original feedstock, the net C sequestration effect is guaranteed by its recalcitrant to decomposition. Zimmermann [44] estimated losses of 3%–26% in a time frame of 100 years, by incubations of biochar from a range of biomass types and combustion conditions.

Further studies are clearly needed to understand all energy and mass balances of such complex chains. As stated by Meyer *et al*. [45] in their literature review on technical, economical, and climate-related aspects of biochar production technologies, more data are needed to provide conclusions about the feasibility of biochar–supply chains. A wide range of costs for biochar production have emerged as well as the GHG balance of biochar systems (between 1054 kg CO_2e and +123 kg CO_2e per t dry biomass feedstock). However, recently available results from an LCA analysis of different energy-supply chains highlighted significant C abatement (CO_2 eq.) both in pyrolysis and pyrogasification plants [46,47] in terms of all GHGs. Han *et al*. [48] calculated GHG reduction of a fast-pyrolysis supply-chain producing fuels with respect to petroleum gasoline, with different impacts depending on the hydrogen sources for pyrolysis oil upgrading and biochar co-product applications.

3. Knowledge Gaps and Research Needs

While the large amount of biochar related scientific publications and reports (a quick search in the SCOPUS database yields more than 750 scientific publications since the year 2000) are consolidating some of the major effects of biochar application, crucial knowledge gaps and research remain to be addressed. A quantitative review of the effects of biochar application to soils, carried out by Jeffery *et al.* [49], showed an overall small significant (on average 10%) benefit of biochar application on crop productivity. Since these effects were more evident in acidic and coarse-texture soils, they concluded that the liming effect, the improved water holding capacity and nutrient availability of the soil were most likely the main mechanisms driving these responses. More recently, Biderman and Harpole [10] evaluated the ecosystem responses to biochar application with a meta-analysis of 371 independent studies from 114 published manuscripts. They found that the addition of biochar to soils resulted, on average, in increased aboveground productivity, crop yield, nutrient availability, microbial biomass and rhizobia nodulation among a broad range of pedo-climatic conditions. The limited number of case studies showing a negative effect of biochar on crop yield [4,49,50] are clearly consolidating the idea that biochar has either a null or positive effect on crop productivity.

Nevertheless, other extensive reviews of available literature [4,51] address the need to answer open key questions, such as the effects of biochar on soil biota [52], the effects of soil erosion on biochar movement [53], particularly through wind erosion, and the long-term health and safety implications for humans, especially in relation to potential contaminants (PAH, Heavy Metals, Chlorinated compounds, *etc.*) [18].

Potential threats of biochar application mainly result from laboratory or field experiments. However, a policy based on large scale application cannot exclude global land-atmospheric feedbacks that might occur. In fact, biochar alters the soil albedo and the surface energy balance [54], reducing the overall climate mitigation benefit [55]. It is recommended that the analysis of the effect of amplified soil warming on local-to-regional atmospheric circulation is evaluated with current Earth-System models taking into account the main land-surface feedbacks due to albedo alteration.

Moreover, the carbonization of large amounts of residues would reduce the incorporation of fresh and more decomposable organic carbon, which is a source of energy for microorganisms. Many studies have already shown a microbial biomass increase due to biochar application, with significant changes in microbial community composition and enzyme activities [51]. However, the underlying mechanisms remain unclear, as the possible long-term effects related to repeated substitution of labile in place of recalcitrant carbon.

4. Conclusions

Biochar is a modern technology based on traditional knowledge from the Amazon. Its systematic application in the EU will require bridging substantial knowledge gaps with targeted research programs. Despite its potential to provide effective responses to policy priorities in the EU, such as soil protection, sustainable waste management, and climate change mitigation, there are still major concerns about long-term effects on ecosystems and human health. The argumentation that the traditional technology of Terra Preta has existed for millennia, and therefore that additional research addressing health and safety implications is not needed, cannot be accepted given the large differences between traditional Terra Preta and modern biochar production.

It is high time for a substantial, policy-relevant, research effort at EU level allowing for the full assessment of all implications of this very promising technology. Once all the knowledge gaps are bridged a solid legislative framework addressing biochar may be developed in order to regulate its use at EU level.

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Conflict of Interest

The authors declare no conflict of interest.

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