LCA of alternative biochar production technologies

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Abstract

This paper investigates the environmental performance of biochar produced using different technologies including: traditional earth kiln; metal ring kiln, Missouri kiln and Missouri with gas recycling. The analysis has been produced using Life Cycle Analysis (LCA) and includes extensive inventory of direct gas emissions during the carbonization stage. The normalized analysis evidence that the impact categories most severely affected are photochemical oxidant formation, human toxicity and climate change. In the case of climate change, impact values ranged between 2773 and 4714 kg CO_2/ton, with lower emissions produced by advanced carbonization technologies due to higher product yields, improved thermal efficiency (which results in reduced combustion of primary products) and elimination of volatile pollutants in the gas condenser and post-combustor. Single point indicator analysis evidences a 33-40 % reduction in environmental impact when using advanced processing methods compared to traditional charcoal production.

Keywords: Biochar, pyrolysis, biomass, LCA

1. Introduction

Slow pyrolysis has been used since pre-industrial times to transform lignocellulosic biomass into charcoal (also referred to as biochar), a renewable solid fuel with improved heating value and fuel properties owing to its reduced water and oxygen contents, lower volatile fraction and higher concentration of elemental and fixed carbon (Emrich, 1985, FAO, 1983, Lehmann and Joseph, 2009). Biochar may be used as a fuel replacement to raw biomass or mineral coals for heat and power generation. In addition, it may find application as a soil conditioner, adsorbent for water treatment, reducing agent in metallurgy, manufacturing of carbon electrodes and medical detoxification (Garcia-Perez *et al*., 2010, Lehmann and Joseph, 2009). Some publications have been produced aimed at quantifying the environmental impacts of charcoal (Alhashimi and Aktas, 2017, Hammond *et al*., 2011, Ibarrola *et al*., 2012, Iribarren *et al*., 2012, Miller-Robbie *et al*., 2015, Rousset *et al*., 2011). Most of these investigations utilize LCA methodology to evaluate potential impacts on certain categories, focusing primarily on global impacts like climate change. However, in most cases they overlook local impact categories like toxicity, photochemical oxidant formation and land acidification, potentially affected by the emission of volatile organic compounds (including polyaromatics) during the pyrolytic stage of the carbonization process. Furthermore, most of these investigations are based on incomplete and/or obsolete inventory data for atmospheric emissions, which do not allow to evaluate the full environmental significance of the carbonization process. Another key issue not sufficiently covered in the scientific literature relates to the application of modern carbonization and pollution abatement technologies, which may improve environmental performance due to increased carbon yields and reduced air emissions.

Figure 1: Charcoal production technologies as investigated in this paper: (1) mould earth kiln; (2) metal ring kiln; (3) Missouri type kiln; (4) modern metal kiln with gas recycling

Depending on capital availability, labor cost, intended output, quality requirements and environmental control limitations, biochar may be produced using a wide range of plant configurations, scales and carbonization technologies. As explained by the European Biochar Foundation in their Guidelines for a Sustainable Production of Biochar (EBC, 2012), most of the charcoal produced worldwide is still produced using traditional technologies where most of the volatile fraction is released into the atmosphere with little control, usually in breach of regulatory emission standards. This is largely the case of Spain, currently one of the main producers and exporters in the European Union (EU), where most of the biochar is produced using traditional low cost batch technologies such as earth mounds kilns, metal ring kilns and Missouri type kilns. Due to the reduced profit margins, continuous operation technologies involving higher capital investments, like multiple hearth furnaces and fluidized bed reactors, are economically viable only in large scale projects or the production of higher value added products like activated carbons (Garcia-Perez *et al*., 2010, Jirka and Tomlinson, 2014, Lehmann and Joseph, 2009). **Error! Reference source not found.** illustrates four of the technologies most used in Spain for biochar production. Traditional earth mound kilns represent the cheapest option in terms of capital cost. These kilns typically have capacities between 5-10 m^3, depending on the purpose they serve (community or commercial production). The wood is stacked and covered with an air-tight layer of earth, incorporating a series of air inlets at the base and an opening at the top (about 20 cm Ø) to control circulation of air and evacuation of exhaust gases. Downsides to this technology include its high labor intensiveness, long processing times (12-15 days including 2-3 days for dehydration, 6-7 days for carbonization and 3-4 days for cooling), limited throughputs per batch, limited product yields (15-20 wt% dry matter basis) and poor homogeneity of final product. A more modern concept in biochar making is steel ring technology. These kilns consist of two interlocking metal rings (typically 200-230 cm Ø and 75-90 cm height, each) stacked one on top of the other with a conical cover for a volumetric capacity of typically between 5-8 m^3. The kilns incorporate air inlets and outlets connected to vertical stacks to facilitate smoke diffusion. Due to its improved temperature control and lower thermal losses, this technology achieves higher carbon yields (20-25 wt%) and reduced processing times (8-10 days). Missouri type kilns are permanent structures similar in concept to rink kilns but larger in size for commercial production of charcoal. The kiln is built using concrete and reinforced steel. Air inlet ports on the base of the kiln are used to control the combustion phase and outlet ports connected to smokestacks are used to vent volatile products. In southern areas of Spain (Extremadura), these kilns are usually designed to accommodate the biomass loading of either one or two 24 ton trailers (35-75 m3). Charcoal yields are similar to those achieved in steel kilns while processing times are lower (7-8 days), thus allowing higher throughput capacities. In order to economize on the use of equipment and labor, Missouri and steel ring kilns may operate as batteries (two to six or more). This strategy also allows the incorporation of gas recycling systems usually consisting of a central flue and after-burner feeding to a common chimney stack. The thermal energy generated in the after-burner during the pyrolytic stage of one set of kilns may be used by other kilns to meet energy demands during the dehydration phase. Additionally, condensation systems may be used to separate low boiling point components, thus reducing gas emissions and generating a pyroligneous oil with the potential to be used as an alternative fuel. The objective of this paper is to quantify potential environmental impacts associated with charcoal using life cycle methodology. The investigation evaluates the effect of using alternative technologies and the incorporation of gas condensation and recycling technology. The analysis incorporates an extensive inventory of gas emissions and takes into consideration not only carbon footprint but also a range of other global and local impact categories.

2. LCA methodology

2.1 Goal and scope definition

This paper describes the environmental LCA of biochar produced using the following technologies: earth mounds, steel ring kilns and Missouri type kilns. The analysis also covers the effect of incorporating a condensation stage and gas recycling technology to treat emissions. The analysis has been performed according to standard methodology ISO 14040-14044:2006. Figure 2 describes the life cycle diagram of the system and the scope of the investigation.

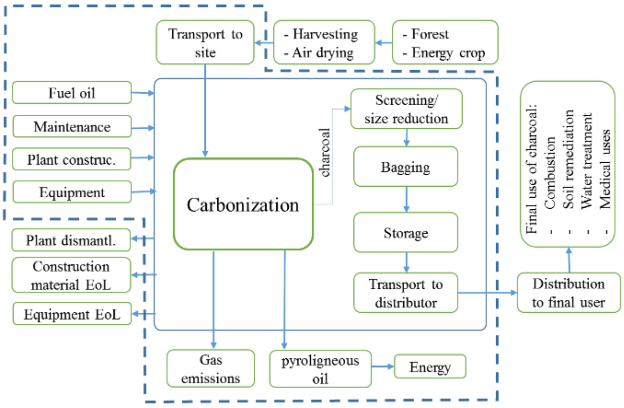

Figure 2: Flowchart describing the charcoal system and the scope of the LCA

The scope of the investigation follows a *cradle to gate* approach including four stages:

- Collection and transportation of biomass feedstocks to carbonization plants.
- Extraction of raw materials and construction of carbonization plants and components.
- Operation of carbonization plants, including gas emissions, waste generation and by-products.
- Processing of final charcoal, bagging and storage.

Table 1: Technical and inventory data for charcoal manufacturing kilns

		Earth mound	Metal ring	Missouri type	Improved Missouri *****
Apparent wood density* (t/m^3)		0.65			
Moisture content* (%)		20			
Transport to kiln (km)		2	5	25	
Transport means		Animal/ human	Animal/ human	Mechanical	
Volumetric capacity (m^3)		7.5	6.5	75	
Loading capacity* (t/cycle)		4.9	4.2	49	
Loading capacity** (t/cycle)		3.9	3.4	39	
Cycles/year***		8	12	18	
Wood processing capacity* (t/yr)		39.0	33.8	878	
Wood processing capacity** (t/yr)		31.2	27.0	702	
Product yield (wt %)**	Charcoal	17.5	22.5	22.5	27.5
	Condensable oils	0	0	0	7
	Gases (by difference)	82.5	77.5	77.5	65.5
Charcoal production capacity** (t/cycle)		0.68	0.76	8.78	10.7
Charcoal production capacity** (t/yr)		5.46	6.1	158	193
Kiln lifetime expectancy (yr)		0	5	8	
Used surface**** (m^2/kiln)		100	50	500	
Previous soil use		Forest			

* fresh wood basis **dry matter basis
*** earth mound and ring kiln = 2 cycles/month 4 month/year; Missouri type = 3 cycles/month and 6 month/year
**** including area for biomass storage and pre-treatment for one kiln
***** including condenser and post-combustion

Table 1 describes the technical characteristics of the systems under consideration. In all cases, biomass has been considered a residue from forest management activities with no associated burdens. Transport of the biomass to the carbonization plant has been assumed to be 2 km for earth mound, 5 km for metal ring and 25 km for Missouri kiln, with longer distances attributed to systems with higher processing capacity. The smaller plants have been assumed to use animal/ human force for biomass transportation while the larger (Missouri type) uses mechanical means (EURO 5 lorry 16-32 t). Wood processing capacity has been calculated considering kiln volume, apparent density of the biomass and number of cycles per year. Fewer cycles have been assumed for traditional kilns than for commercially technologies, taking into consideration the duration of the charcoal season (4-8 months/year) and of the cycles (between 8 - 15 days, including dehydration, carbonization and cooling phases). Charcoal production yields varied between 17.5 % and 27.5 % depending on the characteristics of the system (higher in systems with reduced thermal losses and using gas recycling). Bagging of the final charcoal has been assumed to be done using 10 kg capacity double layer kraft paper bags, each weighing 175 g. Bagging is done manually in the earth mound and ring kilns, and using an electric feeder consuming 1 Wh/kg of charcoal in the Missouri kiln. Foreground inventory data has been provided by PIROECO, a Spanish engineering and bioenergy company based in Extremadura with experience in the field. Background inventory data was obtained and adapted from Ecoinvent 3.2.

Regarding the construction materials of the kilns, the following elements were considered:

- Earth mounds: 8250 kg of clay for the cover of the kiln (80 % reused); manual labor for construction and residual materials (leaves) to mix with clay.
- Steel ring kilns: 290 kg of low alloyed steel for main structure (metal rings and cover); 46 kg of stainless steel for smoke outlets; 50 kg metal working; 15 m gas welding.
- Missouri kiln: concrete (20 m^3), steel (2100 kg in total, including reinforcing steel for structure, low alloyed for door frames and doors, and stainless steel for pipes), metal working (500 kg), clay flue pipes (300 kg), gas welding (15 m), machine operation for construction (60 h) and wood construction for storage (50 m^2).
- Oil condenser and oil recovery system: stainless steel (150 kg); gas welding (10 m); metal working (25 kg); HDPE (320 kg); blow molding (320 kg).
- Post-combustor: steel (35 kg) and metal working (25 kg). No additional use of auxiliary fuels has been considered.

2.2 Quantification of air emissions

Air emissions were obtained from bibliographic sources for biomass carbonization in batch reaction systems, taking into consideration gases (CO_2, CO, CH_4, C_2H_6, C_2H_4, C_3H_6, NO, NO_2) (Bertschi *et al*., 2003), volatile organic compounds (VOC) (including acetic acid, formic acid, formaldehyde, methanol, phenol) (Bertschi *et al*., 2003) and total solid particulates (TSP) (Sparrevik *et al*., 2015). Polyaromatic hydrocarbons (PAH) were calculated from total emission values reported by USEPA (USEPA, 1995) and relative concentrations of the 16 priority PAHs measured for uncontrolled charcoal production reported elsewhere (Mara dos Santos Barbosa *et al*., 2006). The efficiency of the condenser and after-burning system to reduce air emissions depends mainly on its design and operating conditions. For the purpose of this investigation, a conservative approach has been assumed where the condenser employed in the improved Missouri kiln reduced the emission of VOC, PAH and TSP by 80 %, yielding a condensable fraction that represents 7 wt% of the original biomass (dry matter basis). The post-combustion technology reduced the concentration of all oxidizable components (including gases, VOC, PAH and TSP) by a further 80 % (USEPA, 1995). Additional CO_2 emissions resulting from oxidative reactions in the post-combustor were calculated using elemental carbon mass balance. Environmental benefits associated with the use of the condensable fraction (pyroligneous oil) as a fuel may be accounted for using a *system expansion* approach. Displacement of commercial heavy fuel oil may be estimated considering a low heating value (LHV) of 19.5 MJ/kg. Owing to lack of space, this issue has not been included in this paper. Life cycle impact assessment methods ReCiPe Europe H (Midpoint and Endpoint) v1.13 were used to calculate potential impacts on selected environmental categories using characterized, normalized and single point indicators. SimaPro v8.3 software was used to build the models and perform calculations. The system has been analyzed using an attributional approach and adopting as functional unit 1 ton of packed biochar ready for distribution to final users.

3. Results and discussion

Table 3 illustrates the characterized impacts of charcoal produced using different technologies. Regarding carbon footprint, the highest emissions (4714 kg CO_2/ton) were produced by the earth mound. Emissions were reduced by 35-36 % in the steel ring and Missouri kilns due to the higher charcoal yields and improved energy efficiencies

Table 3: Characterized impacts for 1 ton of biochar produced using different technologies

IMPACT CATEGORY	UNITS	EARTH MOUND	STEEL RING KILN	MISSOURI TYPE	MISSOURY + GAS RECYCLING
Climate change	kg CO2 eq	4714	3041	3090	2773
Ozone depletion	kg CFC-11 eq	2.2365E-06	3.4773E-06	1.0056E-05	9.8253E-06
Terrestrial acidification	kg SO2 eq	3.413	2.784	3.026	3.001
Freshwater eutrophication	kg P eq	0.012	0.028	0.026	0.025
Human toxicity	kg 1,4-DB eq	0.240	0.194	0.210	0.208
Photochemical oxidant formation	kg NMVOC	594.8	489.6	486.7	75.8
Particulate matter formation	kg PM10 eq	77.74	60.57	60.78	9.27
Freshwater ecotoxicity	kg 1,4-DB eq	2.62	2.05	2.11	0.16
Agricultural land occupation	m2a	0.749	1.698	1.429	0.992
Natural land transformation	m2	0.324	1.352	1.129	1.017
Water depletion	m3	2.89	4.19	7.45	7.32
Metal depletion	kg Fe eq	140.3	128.4	152.5	148.0
Fossil depletion	kg oil eq	0.870	1.212	3.177	3.084

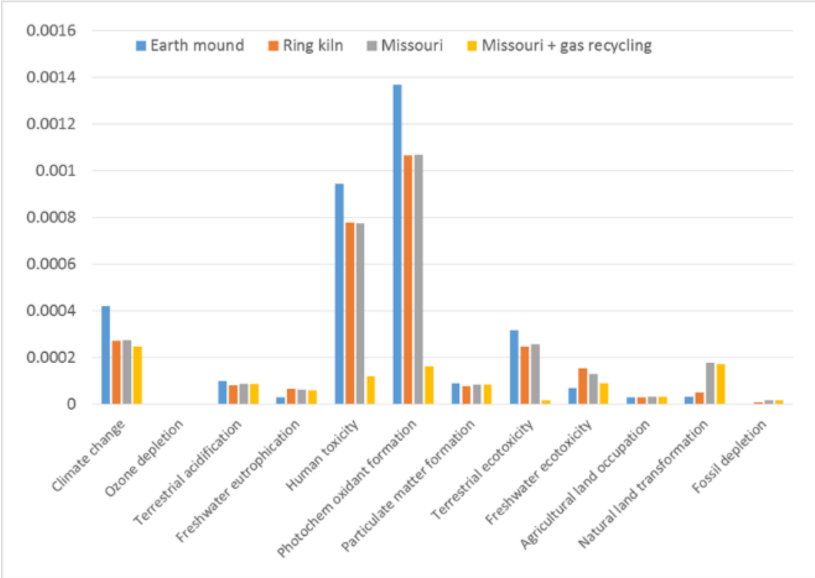

Figure 3: Normalized impacts of charcoal produced using different technologies

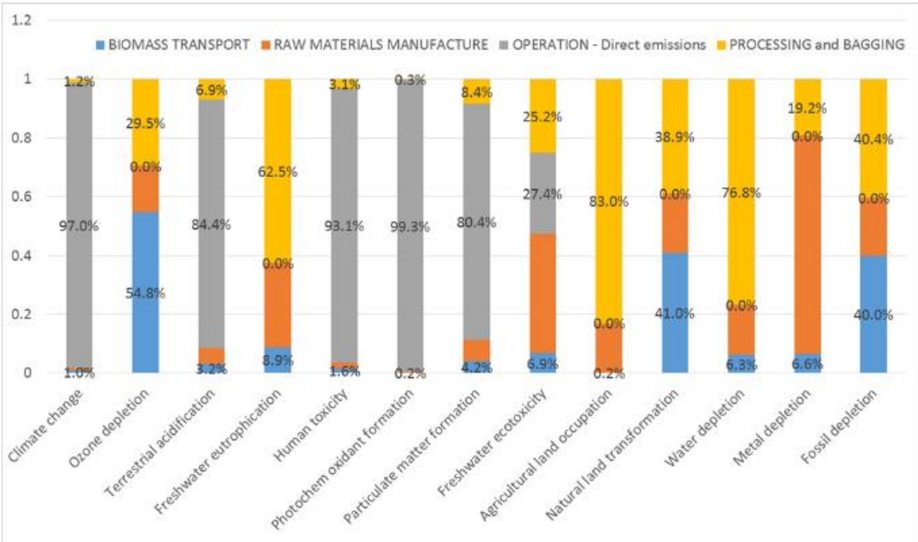

Figure 4: contribution of life cycle stages to different impact categories in the Missouri kiln

(lower combustion requirements). The condenser and post-combustor reduced GHG emissions by a further 10.2 % compared to the conventional Missouri kiln to 2773 kg CO_2/ton. In this latter case, the higher CO_2 emissions derived from the post-combustion stage were compensated by the lower emission of compounds with higher global warming potential (e.g. methane) and the higher charcoal yields. In this reduced version of the paper, the potential use of the condensable fraction as a substitute for heavy fuel oil has not been considered. The Missouri kiln also produced significantly better results in local impact categories related to toxicity, photochemical oxidant formation and particulate matter formation, which are the most severely affected by the system, according to the normalized results. The normalized results in Figure 3 evidence that the impact categories most severely affected by the biochar system (photochemical oxidant formation, human toxicity and climate change) are those associated with direct emissions generated during the carbonization stage. Impact values in all these categories are significantly reduced when using advanced carbonization technologies, particularly with the incorporation of gas recycling in the Missouri kiln. These higher tech options only performed worse in terms of land transformation. Figure 4 illustrates the contribution of different life cycle stages to the environmental impacts of charcoal produced in a conventional Missouri kiln. The results evidence that the origin of the impact on the most severely affected categories (climate change = 97.0 %; photochemical oxidant formation = 99.3 %; and human toxicity = 93.1 %) is primarily attributable to direct emissions during the carbonization process. Other impact categories, like ozone, water and fossil depletion, or freshwater eutrophication, which are not affected by direct emissions, are therefore associated with other activities in the life cycle of the biochar, like biomass transport and charcoal processing and bagging (due to the use of mechanical vehicles and electricity use in the automatic processing and bagging stage). However, the severity of these impacts is very low compared to the ones previously mentioned. The

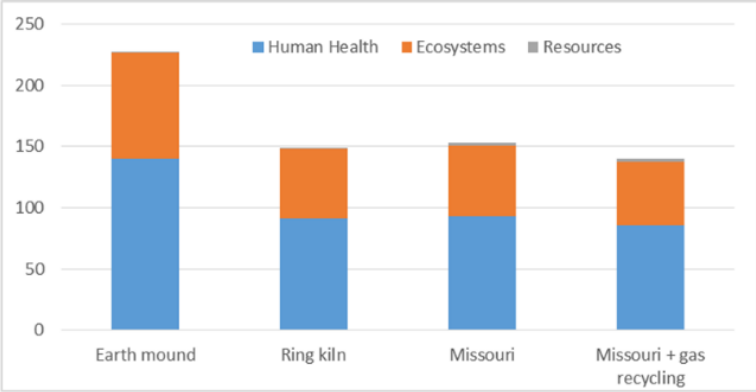

Figure 5: Single point impact indicator for biochar produced using different technologies

contribution of extraction of raw materials and construction to the environmental performance of the system is insignificant. The single point impact determinations shown in Figure 5 evidence the benefits of using improved technologies for charcoal manufacturing. The worst results were produced by the earth mound, due to the low charcoal yield and high direct emissions affecting human health and damage to ecosystems to a lower extent. The best performance was achieved by the Missouri kiln with gas recycling.

4. Conclusions

The environmental performance of charcoal is strongly affected by the characteristics of the technology employed in its manufacturing. Impact on climate change ranged from 4714 kg CO_2/ton in earth mounds to 2773 kg CO_2/ton in Missouri kiln equipped with condenser and post-combustion technology. This is due primarily to higher product yields, improved thermal efficiency (which results in reduced combustion of primary products) and elimination of volatile pollutants in the condensation and post-combustion stage. The normalized results evidence that the impact categories most severely affected by the charcoal system are local categories (photochemical oxidant formation, human toxicity and terrestrial ecotoxicity) and global categories like climate change. In order to complete this investigation and facilitate decision making, additional work should be carried out to determine economic and social impacts associated with the alternative technology scenarios.

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