Biomass and Bioenergy 101 (2017) 35–43

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Life-cycle assessment of biochar production systems in tropical rural areas: Comparing flame curtain kilns to other production methods

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A R T I C L E I N F O

Article history:
Received 29 December 2016
Received in revised form
28 March 2017
Accepted 2 April 2017

Keywords:
Biochar
Life cycle assessment
Cook-stove
Gasifier
Retort kiln
Earth-mound kiln
Flame curtain Kon Tiki kiln
Gas emissions

A B S T R A C T

A life-cycle assessment (LCA) using end point methods was performed for the generation and sequestration of one kg biochar by various pyrolysis methods suitable for rural tropical conditions. Flame curtain kilns, a novel, simple and cost-effective technology of biochar generation, were compared to earth mound non-improved kilns, retort kilns with off-gases combustion, pyrolytic cook-stoves allowing the use of the gas flame for cooking purposes, and iv) gasifiers with electricity production. The impact categories of climate change, particulate matter emissions, land use effects, minerals and fossil fuels were combined to provide the overall impact of biochar generation.

In the LCA ranking, earth mound kilns were shown to have negative potential environmental impacts because of their gas and aerosol emissions. Flame curtain kilns had slightly lower potential impact than retort kilns and much lower impact than earth-mound kilns because of the avoidance of start-up wood and low material use and gas emissions. Making biochar from flame curtain kilns was observed to be environmentally neutral in a life-cycle perspective, as the production emissions were compensated for by carbon sequestration. Pyrolytic cook-stoves and gasifiers showed the most positive potential environmental impact in the LCA due to avoided firewood consumption and emissions from electricity generation, respectively.

The generation and sequestration of biochar *per se* by flame curtain kilns was not found to result in direct environmental benefits. Co-benefits in the form of rural applicability, cost-efficiency and agricultural effects due to soil improvement are needed to warrant biochar implementation by this method.

1. Introduction

Biochar is produced by the thermal treatment (>350 °C) of biomass under low-oxygen conditions and provides a method to sequester carbon. Biochar can be used for the immobilization of contaminants in water, soils or sediments [1–4], as well as for the improvement of crop productivity in weathered and eroded soils [5,6]. The production of biochar in modern industrial devices can be a highly controlled process with low gas emissions [7]. However, achieving the same results under rural tropical conditions, i.e., with poorly maintained technologies in very low income settings, is more challenging [8]. Emitted gases during the process include methane (CH_4), carbon monoxide (CO) and aerosols (smoke; $PM_{2.5}$ and PM_{10}), nitrogen oxides (NO and NO_2, together NO_x), as well as non-methane volatile organic matter (NMVOC), in addition to hydrogen. CO, aerosols and NO_x are deleterious to human health [9–11], and methane and aerosols can exacerbate anthropogenic radiative forcing [12,13]. Several biochar production methods for low-income rural conditions exist. Traditionally, *earth mound or earth covered pit kilns* have been used most frequently. They are free of investment cost, merely requiring some poles and sand to cover the pyrolyzing biomass. However, they are slow (several days [14]), and generate significant gas/aerosol emissions [15,16]. *Retort kilns* (Fig. S1) involve a higher material investment and partially combust

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http://dx.doi.org/10.1016/j.biombioe.2017.04.001
0961-9534/

pyrolysis gases, reduce gas emissions by about 75% and have relatively high conversion efficiencies of 30–45% [17]. *Biochar-producing pyrolytic cook-stoves* such as TLUDs (Top-Lit Up-Draft stoves) and Anila stoves [18] can generate biochar while providing heat for cooking. Advantages include that they burn cleanly thus reducing indoor air emissions, can use various biomass residues as feedstock and are fuel-efficient. Pyrolytic gases are mostly combusted in the flame front, reducing emissions of CO, CH_4 and aerosols by around 75% [19,20] compared to open-fire or three-stone cooking. Even though the epidemiological evidence behind the relationship between indoor air emissions and premature death rates is scant [21], this can be considered an advantage. *Modern gasifier pyrolysis units* come at a much higher investment cost but lead to the lowest emission factors and allow for the generation of electricity avoiding electricity generation by off-grid fossil-fuel generators [7].

A recent development has been the introduction of the *Kon-Tiki* flame curtain kiln [8,22], which is fast compared to traditional kilns (hours instead of days), cost-effective and easy to operate. Flame curtain kilns come in two basic concepts: as a conical, all-steel deep-cone bowl (Fig. S1) and as a simple soil pit, consisting of a conically shaped hole in the ground which can be dug in a few hours and is essentially free of investment cost (Fig. S1). In a previous paper, we found the gas and particle emissions of various flame curtain kiln designs, including the soil pit design, to be universally low, lower still than those of retort kilns, especially for CO [22].

Life-cycle assessment (LCA) can compare the overall environmental impact of various alternatives for biochar generation and use. In several LCAs biochar production has been studied and various production methods have been compared. Ibarrola, Shackley [23] observed that slow pyrolysis systems offer better performance in terms of LCA climate impacts than fast pyrolysis and gasification, whereas gasification achieved the best electricity generation outputs. Peters, Iribarren [7] found that the best use of biochar in an overall LCA perspective is to use it as a replacement of fossil coal in power plants, provided the biochar is made in a modern, ultralow emission pyrolysis unit. In contrast, the overall environmental life cycle impact of biochar made in retort kilns under rural low-income conditions (Indonesia) was found to be positive when used in agriculture (mainly due to carbon sequestration), but negative when used as a fuel (mainly because air emissions from biochar production is not outweighed by lower emissions during use) [24]. In a study on rural Zambian conditions it was found that biochar amendment only resulted in positive overall environmental impacts when pyrolysis gas emissions are relatively low (such as in retort kilns or pyrolytic cook-stoves) and agricultural effects strong so that the negative impact of energy-intensive mineral fertilizers is spread out over more units of crop yield [25].

Even though the earlier LCAs performed point to benefits of both low production emissions and secondary benefits from fossil fuel substitution, different system boundaries makes it difficult to generalize between studies. In the present work we wished to compare various biochar generation technologies for rural condition on an equal basis. We did this for the above mentioned biochar technologies, with a special focus on comparing the novel flame curtain technology to the previously studied ones (earth-mound, retort, pyrolytic cook-stove) as well as to gasifiers. The study of flame curtain kilns is important since they have been implemented in 67 countries (http://www.ithaka-institut.org/en/ct/113-World-of-Kon-Tiki). Thus we carried out an LCA to compare the environmental burden or investment from production of biochar with the potential environmental benefits of carbon sequestration and/or heat generation from the pyrolysis utilized for cooking or electricity generation.

The goal of the work was thus not to further develop LCA techniques, but rather use it as a tool to compare various biochar production alternatives. The low middle-income context of Indonesia was taken as a case, but the trends are probably similar for most rural developing country situations. This comparison will aid in understanding the potential environmental impact of various technologies for biochar preparation under rural conditions in developing or lower-middle income countries where poorly maintained, artisanal technologies often prevail.

2. Materials and methods

2.1. Goal and scope

The goal of this LCA was to compare the environmental impact from the preparation of biochar under rural conditions in low-income or lower middle-income countries. Five different pyrolysis methods were compared, two low temperature technologies (i,ii) and three high-temperature technologies (iii, iv, v): (i) earth-mound non-retort earth mound kilns; (ii) retort kilns (Table S2), (iii) novel “Kon Tiki” flame curtain kilns, where both the all-steel deep cone variety and the simple soil pit variety were tested (Table 1); (iv) micro pyrolytic cook-stoves allowing the use of the gas flame energy for cooking purposes, and (v) gasifiers where the heat from the combustion of pyrolysis off-gases is utilized for electricity production (for further details, see SI). The functional unit was the preparation and sequestration of one kg biochar. All aggregated impact categories and their units are presented in Table 1.

2.2. System boundaries

Biochars produced by different technologies were compared by including the pyrolysis (biochar production) process, carbon sequestration and if applicable avoided electricity production or avoided wood combustion for cooking purposes in the system. The feedstock used to produce biochar was assumed to be a woody shrub or agricultural residue without any alternative value. No environmental effect from decomposition of feedstock was foreseen, assuming aerobic conditions and no stockpiling. We assumed no net emissions of carbon dioxide since the biogenic carbon uptake and release from the feedstock is taking place within approximately one growth season.

Avoided burden approaches were applied to include the electricity produced during biochar production using a gasifier, and the wood consumption avoided by cooking on a biochar-generating stove. In a rural location in a developing country the avoided source of electricity was assumed to be a house-hold sized diesel-fuelled generator (Tables S8–12). This also makes the data more universally applicable since the environmental effects of fabricating, transporting and combusting one litre of diesel are more constant than the environmental impacts of the electricity mix in one particular country. As this study focused entirely on biochar generation, the co-benefits of biochar, e.g. in agriculture or remediation, were outside its scope.

2.3. Inventory analysis

For earth-mound, retort and flame curtain kilns, primary data of gases emitted during pyrolysis were taken from measurements previously conducted in our projects in Zambia, Indonesia and Nepal [16,22] (Tables S4–6). Literature values and information from manufacturer were used for pyrolytic cook-stoves [19] and gasifiers (Tables S7–8).

Differences in biochar yield due to different technology