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Short Communication

Flame curtain kilns produce biochar from dry biomass with minimal methane emissions

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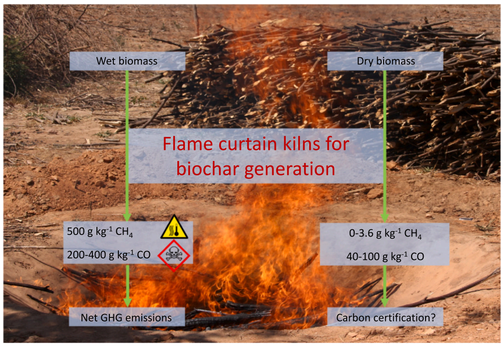
HIGHLIGHTS

- Gas and particle emissions of two flame curtain biochar kilns were compared.
- Almost no methane emissions for dry feedstock
- High methane emissions for wet feedstock
- Certification of low-tech biochar made from dry biomass should not be objected to on the grounds of methane.

GRAPHICAL ABSTRACT



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ABSTRACT

Flame curtain kilns have emerged as the preferred biochar technology for smallholders but reported methane emissions (30 g kg^{-1} biochar) have impeded carbon certification. Here, for flame curtain kilns we show almost no methane (0–3.6 g kg^{-1} biochar) emissions for dry (<15 % moisture) feedstock consisting of twigs and leaves. Wet feedstock (>40 % moisture) however generated significant methane (>500 g kg^{-1} biochar), underscoring that feedstock preparation is decisive for the carbon balance. Even for dry feedstock, both aerosol and CO emissions were significant (21–82 and 40–118 g kg^{-1} biochar, respectively). The data demonstrate that certification of low-tech biochar made from dry twigs and leaves should not be objected to on the grounds of methane. Careful selection of feedstock and potential after-combustion of the syn-gases are probably needed to avoid CO and aerosol emissions. More data are needed on methane emissions of other dry feedstocks.

1. Introduction

In the tropics biochar has been suggested for pyrogenic carbon capture and storage (PyCCS) (Schmidt et al., 2019) and to improve crop productivity, especially in weathered soils (Lehmann and Rondon, 2006). Carbon credits could create direct incentives for small holder

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farmers to produce biochar (Schmidt et al., 2019; Scholz et al., 2014). However, artisanal production of biochar by small holders has not figured prominently in the emerging markets for negative emissions (Aquije et al., 2021).

The *Kon-Tiki* flame curtain kiln has been adopted in over 100 countries (Cornelissen et al., 2016; Jayakumar et al., 2023; Kalderis et al., 2020), increasing biochar implementation in developing nations, though still mostly small scale. Flame curtain kilns are low-cost and allow for on-farm production of high-quality char (Kalderis et al., 2020; Tsubota et al., 2021). The most economical version is a simple soil pit (Fig. 1a, b). Reported emissions from Kon-Tiki kilns are lower than those from traditional and retort kilns for CO and NOx, but not for methane and aerosols (Cornelissen et al., 2016).

Pyrolysis gases such as methane are combusted in the flame curtain above the pyrolyzing biomass. However, the emerging platforms that certify negative emissions from biochar have been reluctant to include biochar from flame curtain kilns (Aquije et al., 2021). This may be related to an emission factor of 28.5 g of methane per kg of biochar produced that we reported in 2016 for the pyrolysis of twigs with 25 % moisture (Cornelissen et al., 2016). Other toxic and/or greenhouse gases emitted include carbon monoxide (CO), aerosols (smoke; $PM_{2.5}$ or PM_{10}), nitrogen oxides (NO_x), as well as non-methane volatile organic carbon (NMVOC) (Cornelissen et al., 2016).

Here we report the results of a study in which we tested the hypothesis that the pyrolysis of sufficiently dry feedstock would lead to significantly lower methane emissions. Gas and particle emissions of two flame curtain kilns were compared, a conical Kon Tiki soil pit (Cornelissen et al., 2016; Kalderis et al., 2020; Pandit et al., 2017; Schmidt et al., 2017) and a batch pyrolyzer built for the UN funded Biochar for Sustainable Soils (B4SS) project, modified for continuous operation (Fig. 1c, d). Emissions were measured in both kilns using wet vs. dry and leaves vs. twigs, respectively, as feedstock. Emissions were measured continuously across the complete pyrolysis cycles.

2. Materials and methods

2.1. Flame curtain principle

Both the Kon Tiki, and the modified batch pyrolizer (el Horno; Fig. 1) use a flame curtain to catch rising pyrolysis gases and combust them before emission to the atmosphere. Both ovens were fed manually by experienced operators at ≈5-min intervals to ensure the integrity of the flame curtain.

Key differences between the Kon Tiki and el Horno (Fig. 1) include the fact that the latter possesses an internal heat shield and is fully insulated to maintain elevated temperatures within the oven. El Horno also possess a ventilation system powered by a 1 hp fan that controls air flow into the base of the combustion chamber (the pyrolysis zone), the mid-section of the combustion chamber (the flame curtain) and into a heat exchanger used to capture energy. In both ovens the pyrolysis process was ended by quenching with water. The correct end time of the process was indicated by white ashes forming on top of the pyrolyzing biomass (Cornelissen et al., 2016; Schmidt and Taylor, 2014). The temperature in the main pyrolysis zone was monitored via thermocouples. In el Horno, temperature was also monitored in the flame curtain.

2.2. Moisture and carbon content

Moisture in the feedstock was measured with a Protimeter Timbermaster BLD5609 (1 % accuracy). Three feedstock moisture categories were used when making biochar in the Kon Tiki: dry (14.7 ± 3.4 %, n = 36), half-dry (29.0 ± 12.4 %, n = 12) and wet (41.0 ± 11.6 %, n = 31). Only dry and wet feedstock was used in el Horno. Carbon content in feedstock and biochar was measured according to method described in Cornelissen et al. (2016).

2.3. Kiln operation

All runs commenced with 20–30 kg of dry feedstock. For both runs with dry biomass (Kon Tiki and el Horno), dry twigs (C-content 45.9 ±

Fig. 1. a) Flame curtain "Kon Tiki" soil pit kilns in Zambia used to produce 100 t of biochar for a macadamia plantation, b) the soil pit kiln used for emissions testing in this study, c) el Horno, and d) schematic of el Horno.

0.3 %; n = 3) and leaves (C-content 49.6 ± 2.2 %; n = 3) were added at 5-min intervals. For the Kon Tiki run with wet biomass, half-dry biomass was added for 31 min (Table 1). Then, wet biomass was added for another 34 min. For the el Horno run with wet biomass, wet biomass was added after the first 20–30 kg of dry feedstock had been pyrolyzed. Emitted gases were sampled in a conical chimney above the Kon Tiki kiln. Variations in flow laminarity would cause variations in absolute gas concentrations, but since all emissions were related to CO_2 concentrations for each data point, this did not influence the emission factor data.

2.4. *Pyrolysis temperature*

With dry feedstock, temperatures ranged from 600 °C to 810 °C (Kon Tiki) and from 650 °C to 859 °C (el Horno). Temperatures plunged after the addition of wet feedstock, to 350–412 °C for el Horno and 540 °C for the Kon Tiki.

The gases analyzed were CO_2, CO, CH_4, NMVOC, NO_x and aerosols (total suspended particles, TSP, derived from PM_{10}). Instrumentation, carbon mass balance calculations and statistics were as described in previous work (Cornelissen et al., 2016; Sparrevik et al., 2015). Briefly, a Microtector II 6460 was used to analyze carbon dioxide (CO_2) and methane (CH_4) by infrared sensors. CO_2 had a detection limit of 0.1 % and CH_4 of 0.005 % [(0.1 % of the Lower Explosive Limit (5 %)]. Non-methane volatile organic components (NMVOC) were measured by photoionization detection (PID) with a detection limit of 0.1 ppm. The PID was calibrated using isobutene. Carbon monoxide (CO) and nitric oxide (NO) were analyzed with a Kigaz 300 flue gas analyzer by internal jacket type electrochemical sensors. Detection limits were 1 ppm for both sensors. For CO values above 8000 ppm the Kigaz instrument internally dilutes the gas stream to be able to measure concentrations up to 50,000 ppm. The instrument converts NO to generic nitric oxides (NO_x) by applying a conversion factor of 1.03, thus assuming that 97 % of NOx consists of NO. Particles in the form of PM_{10} were analyzed with a Thermo Scientific pdr-1500 instrument by use of photometric detection of particles (detection limit 0.1 μg/m^3).

3. Results and discussion

3.1. *Biochar yields*

Biochar yields were 24.5–24.8 % dw for the dry biomass (both in el Horno and the Kon Tiki) and 19.6 % and 21.2 % for the wet biomass in the Kon Tiki and el Horno, respectively (Table 1), similar to the 22 % reported for Kon Tiki kilns previously (Cornelissen et al., 2016), and slightly lower than the 28 % for soil-pit kilns previously reported (Jayakumar et al., 2023). C and H contents of the biochars were 81–84 % and 2.6–2.9 % with no clear trends with moisture content or technology (Table 1).

3.2. *Gas emission factors*

The most important result of this study was that there were non-detectable to low methane emissions for both kilns when feedstock was dry or half-dry (0.0 g kg^{-1} biochar for the Kon Tiki; 3.6 g kg^{-1} biochar for el Horno; Table 1), confirming our hypothesis. Note that the latter value is a semi-quantitative number derived from three distinct methane spikes during biomass addition and during quenching, each lasting around 20 s and averaged over the whole duration of the experiment (107 min). Such spikes were not observed during the Kon Tiki dry and half-dry feedstock runs. Also, a check setting methane emissions at each time point equal to LOQ/2 (0.0025 %) shows that non-quantifiable emissions represent <5.5 g kg^{-1} biochar. The methane emission factors for dry feedstock (0–3.6 g kg^{-1}) were lower than those in our previous paper on Kon Tiki kilns (28.5 g kg^{-1} (Cornelissen et al., 2016)). This is probably caused by the lower moisture content of the currently used dry twigs (14.7 %) than of those used in the previous study in Nepal (25 %). In contrast, pyrolysis of wet feedstock led to significant methane emissions of >500 g kg^{-1} biochar for both kilns. This underscores the importance of using dry feedstock to keep the flame curtain intact. Methane emissions of 600 g kg^{-1} biochar correspond to 15 kg CO_2-eq kg^{-1} biochar (using the 100-year global warming potential of methane of 25 (Boucher et al., 2009)), by far exceeding the approximately 2.0–2.5 kg CO_2-eq sequestered by biochar amendment to soil (Yang et al., 2021).

The large interquartile ranges in all emission factors do not reflect a lack of data but a high variability of gas emissions during operation, caused by variations in burning conditions during the individual runs.

Emission factors for CO (between 40 and 100 g kg^{-1} biochar) were close to those previously reported for Kon-Tiki kilns (52 g kg^{-1} (Cornelissen et al., 2016) and 3–24 g kg^{-1} (Jayakumar et al., 2023)). CO was a little lower for el Horno (19–68 g kg^{-1}) than for the Kon Tiki (60–203 g kg^{-1}), probably because of the ventilation system ensuring oxygen flow to the flame curtain, and hence better conversion of CO to CO_2. CO emissions were lower than those for traditional kilns (351 g kg^{-1}), comparable to those for retort kilns (148 g kg^{-1}) and TLUDs (94 g kg^{-1}). They were much higher than those for advanced pyrolysis systems with after-combustion (<4.5 g kg^{-1}). For NO_x the opposite trend was observed, with slightly higher but still modest emissions for the el Horno (0.83 g kg^{-1} biochar) than for the Kon-Tiki (0.01 g kg^{-1} biochar). This is attributed to a combination of the higher temperature in el Horno due to its insulation and heat shield, and the improved access of oxygen, increasing the air-to-fuel ratio favoring NO_x over CO formation (Cornelissen et al., 2016).

Aerosols (TSP; PM_{10}) were in the order of 20–50 g kg^{-1} biochar and showed no clear trend with feedstock moisture. They were above values previously reported for both Kon Tiki and other kilns (around 10 g kg^{-1} biochar; Table 1). This is tentatively explained by leaf litter being used in the present work (which was not used in the previous studies). Notably, these emissions factors were also higher than those reported for traditional kilns, retort kilns and TLUDs (19, 11 and 7 g kg^{-1}, respectively). This indicates that feedstock type rather than moisture content is decisive for aerosol emissions from various kilns with varying principles. These data show that Kon Tiki kilns are not necessarily the cleanest kilns when regarding aerosol emissions. It also underscores the need for a more extensive data base of emission factors for various feedstocks. Syngas combustion such as in Pyreg and large-scale reactors strongly reduces the aerosol emissions (0.05–2.5 g kg^{-1}).

Emission factors of NMVOC were, along with methane, lower for Kon Tiki and el Horno kilns (0.79 and 1.9–2.1 g kg^{-1}, respectively) than for previously studied traditional kilns, retort kilns and TLUDs (53, 7 and 274 g kg^{-1}, respectively). Advanced pyrolysis units with after-combustion emit very low NMVOC (< 0.33 g kg^{-1}).

3.3. *Implications*

The flame curtain kiln offers multiple advantages: i) gas and aerosol emissions are relatively low compared to other low cost biochar and charcoal production technologies, but not to advanced technologies for production at scale (Table 1); ii) construction and operation are easier and more economic compared to retort kilns; iii) pyrolysis is much faster (h) than for most traditional and retort kilns (days); and iv) heat energy can be recovered.

It is in everyone's interest that smallholders convert waste biomass into biochar. For example, coffee is grown on about 12.5 million farms globally. 95 % of these orchards span <5 ha (Barreto Peixoto et al., 2023). Degradation of soils on which coffee is grown leads to expansion of the agricultural frontier (Barreto Peixoto et al., 2023; Barrett and Bevis, 2015), and this into highly diverse montane tropical rainforest. Financial incentives for low-tech biochar production on coffee farms could diminish or even reverse the loss of soil fertility (Barreto Peixoto et al., 2023). This in turn could reduce the rate at which the agricultural

Table 1

Moisture contents (%), biochar yields (%), biochar C contents (%), biochar carbon-normalized yields (%), emission factors (g kg^{-1} biochar) of CO_2, CO, CH_4, TSP [aerosols, from particulate matter <10 μm (PM_{10})], non-methane volatile organic carbon (NMVOC), and the sum of nitrogen oxide and nitrogen dioxide (NO_x). Median values (upper numbers) and interquartile ranges (IQR — numbers in brackets) per run. Literature values on emissions from Kon Tiki flame curtain kilns, traditional non-improved kilns, retort kilns with syngas circulation and combustion, TLUDs, and high-technology medium- and large-scale reactors.

Run	Feedstock Moisture	Bio-mass in	Biochar out	Dura-tion	Biochar yield	Biochar C	Biochar H	n[a]	CO_2	CO	NMVOC	CH_4	TSP	NO_x
	%	kg dw	kg dw	min	%	%	%		g kg^{-1} biochar					
Kon Tiki soil pit dry	14.7 ± 3.4	85.3	21.2	51	24.8	81.2 ± 1.6	2.62 ± 0.30	25	3633	101 (60–181)	0.79 (0.00–2.82)	0.0 [h]	62 (29–97)	0.012 ± 0.035
Kon Tiki soil pit half-dry	29.0 ± 12.4	82.1 [b]	17.4[b]	31	21.2[b]	84.0 ± 1.1[b]	2.80 ± 0.24	18	4668	118 (84–203)		0.0 [h]	69 (33–87)	0.004 ± 0.008
Kon Tiki soil pit wet	41.0 ± 11.6	82.1[b]	17.4[b]	34	21.2[b]	84.0 ± 1.1[b]	2.80 ± 0.24	16	3049	206 (145–273)		605 (485–996)	21 (16–39)	0.000
El Horno isolated kiln dry	14.7 ± 3.4	536.7	131.8	147	24.5	83.9 ± 2.5	2.65 ± 0.19	24	3845	40 (19–68)	1.89 (1.08–2.48)	3.6[g,h]	32 (26–52)	0.80 (0.35–1.56)
El Horno isolated kiln wet	41.0 ± 11.6	125.8	24.7	60	19.6	80.9 ± 1.0	2.87 ± 0.30	12	3381	373 (220–514)	2.16 (0.79–3.18)	579 (495–1128)	82 (48–108)	0.000
Kiln literature														
Kon Tiki soil pit[c]	25.0				22.0	76		190	3944	32	5.3	28.5	9.3	0.55
Traditional kilns[d]	12.2				30.1	55		40	2375	351	53	49	19	2.2
Retort kiln[d]	12.6				32.0	67		40	2602	148	7	35	11	1.7
TLUD[e]	3.4				–	–		–	–	94	274	40	7	0.0
Medium-scale Pyreg® reactor[e]	20.9				25.2	78		7	4394	4.5	0.33	0	2.5	0.6
Large-scale reactor[f]	<10				–	–		–	3010	$3 \cdot 10^{-7}$	0	0	0.05	0.7

[a] n is number of emission measurements the median and IQR were based on.

[b] Average for half-dry and wet biomass since these were measured in one run.

[c] Data from Cornelissen et al. (2016), measured with the same instruments and setup. CO data: average for Jayakumar et al. (2023) (3–24 g kg^{-1}) and Cornelissen et al. (2016) (52 g kg^{-1}).

[d] Average of two literature datasets where each data set was given equal weight (Sparrevik et al., 2015; Pennise et al., 2001), measured with the same instruments and setup in Sparrevik et al. (2015).

[e] Data from Sørmo et al. (2020) measured with the same instruments and setup.

[f] Data from Peters et al. (2015).

[g] Approximate value based on three spikes each lasting around 20 s and averaged over the whole duration of the run (107 min).

[h] <5.5 g kg^{-1} biochar when setting measurements at each time point to LOQ/2 (0.0025 %).

frontier expands into this critical biome with positive implications for our planet's imperiled biodiversity. At the same time, although individual coffee farms are small, in aggregate they represent a large opportunity for carbon sequestration if we could find a viable mechanism to incentivize biochar production by coffee farmers. Also, each year >30 million tonnes of olive tree pruning waste in the Mediterranean region remain unexploited and most of this is openly burned in the fields. Such waste could also be used for biochar production using Kon-Tiki equipment on-site (Cuevas et al., 2019; Fawzy et al., 2022).

The emission results in the present work demonstrate that certification of low-tech biochar made from dry biomass should not be objected to on the grounds of methane. Nevertheless, challenges to certifying biochar production in remote regions and/or by individual farmers remain legion. Transaction costs will be large (Cacho et al., 2005). The fact that dry biomass is essential for a negative carbon balance is also an important complication in the humid tropics. Aerosol emissions were found to be significant also for the Kon Tiki and el Horno kilns. Also, uncertainty exists around potential methane emissions from other feedstocks even when dry. Thus, more studies are needed on the gas and aerosol emissions from the pyrolysis of various feedstocks using artisanal methods, especially for the high-volume wastes such as maize cobs (Obia et al., 2016), olive prunings (Cuevas et al., 2019; Fawzy et al., 2022) and coffee husks (Barreto Peixoto et al., 2023) preferably measured as a function of feedstock humidity.

Despite existing challenges, artisanal biochar production could have a large positive impact on both climate, biodiversity and smallholder livelihoods. These are compelling reasons to find a way forward and financially incentivize low tech biochar in the tropics.

CRediT authorship contribution statement

Gerard Cornelissen: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Roles/Writing – original draft.

Erlend Sørmo: Conceptualization; Formal analysis; Investigation; Methodology; Validation; Writing – review & editing.

Ruy Korscha Anaya de la Rosa; Funding acquisition; Methodology; Writing – review & editing.

Brenton Ladd; Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Visualization; Roles/Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gerard Cornelissen reports financial support was provided by Norwegian Geotechnical Institute. Gerard Cornelissen reports a relationship with Norwegian Geotechnical Institute that includes: employment.

Data availability

Data will be made available on request.

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