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Emission Factors for Biochar Production from Various Biomass Types in Flame Curtain Kilns

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Abstract: Simple and low-cost flame curtain ("Kon-Tiki") kilns are currently the preferred biochar technology for smallholder farmers in the tropics. While gas and aerosol emissions have been documented for woody feedstocks (twigs and leaves) with varying moisture contents, there is a lack of data on emissions from other types of feedstocks. This study aims to document the gas and aerosol emissions for common non-woody feedstocks and to compare emissions from finely grained, high-lignin feedstock (coffee husk) with those from coarser, low-lignin feedstocks (maize cobs, grass, sesame stems). Throughout each pyrolysis cycle, all carbon-containing gases and NO_x were monitored using hand-held sensitive instruments equipped with internal pumps. Carbon balances were used to establish emission factors in grams per kilogram of biochar. The resulting methane emissions were nearly zero (<5.5 g/kg biochar) for the pyrolysis of three dry (~10% moisture) maize cobs, grass, and a 1:1 mixture of grass and woody twigs. For sesame stems, methane was detected in only two distinct spikes during the pyrolysis cycle. Carbon monoxide (CO) and aerosol (Total Suspended Particles, TSP) emissions were recorded at levels similar to earlier data for dry twigs, while nitrogen oxide (NO_x) emissions were negligible. In contrast, the pyrolysis of finely grained coffee husks generated significant methane and aerosol emissions, indicating that technologies other than flame curtain kilns are more suitable for finely grained feedstocks. The emission results from this study suggest that certification of biochar made from dry maize, sesame, and grass biomass using low-tech pyrolysis should be encouraged. Meanwhile, more advanced systems with syngas combustion are needed to sufficiently reduce CO, CH_4, and aerosol emissions for the pyrolysis of finely grained biomasses such as rice, coffee, and nut husks. The reported data should aid overarching life-cycle analyses of the integration of biochar practice in climate-smart agriculture and facilitate carbon credit certification for tropical smallholders.

Keywords: emissions; flame curtain kiln; Kon Tiki kiln; sesame; maize; grass; methane

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1. Introduction

Biochar is a promising tool for carbon dioxide removal (CDR) through pyrogenic carbon capture and storage (PyCCS) [1] which can also improve crop productivity [2] and bind soil contaminants [3]. For resource-poor smallholders in the tropics, cheap artisanal methods such as the "Kon-Tiki" flame curtain kilns are probably the most feasible for producing biochar in the foreseeable future [4]. Soil improvements in the longer term may not be a strong enough incentive for biochar making due to insecure land tenure arrangements and hand-to-mouth existence [5]. Carbon credits could create a more direct

incentive for smallholder farmers to produce biochar, especially as a complement to the potential productivity benefits [1,6].

Flame curtain kilns have been adopted in many countries [4,7–12]. They are low-cost, can be operated on-farm, and can be used intermittently based on feedstock availability [9,10,13]. The most economical version is a simple, cone-shaped soil pit [10,11]. During production, pyrolysis gases, most importantly methane, are combusted in the flame curtain above the pyrolyzing biomass. However, carbon certification platforms have been reluctant to include biochar from flame curtain kilns [14]. This reluctance may be related to concerns over emissions of toxic and/or greenhouse gases, including methane (CH_4), carbon monoxide (CO), aerosols (smoke; $PM_{2.5}$ or PM_{10}), nitrogen oxides (NO_x), and non-methane volatile organic carbon (NMVOC) [7]. Methane is a strong greenhouse gas with a 100-year global warming potential (GWP) of 25 [15]. While highly toxic, CO is a weak greenhouse gas, as it has been shown to be further oxidized to CO_2 in the atmosphere [16]. A GWP of 1.0 to 3.0 has been quantified for CO [17]. Aerosols can be both a driver and a dampener of global warming and annually cause millions of preliminary deaths from cooking on wood fires [18].

Earlier, we documented that the pyrolysis of sufficiently dry twigs and leaves in flame curtain kilns led to almost zero methane, NMVOC, and NO_x emissions, as well as significant but acceptable CO and aerosol emissions (21–82 and 40–118 g kg^{-1} biochar, respectively) [19]. An important remaining knowledge gap is the lack of emission data for other feedstocks. Of special importance are feedstock biomass types for which other uses are limited, such as maize cobs, grasses, and many husk types, and/or those that are left decaying in large mounds leading to methane emissions [20], such as rice and coffee husks as well as cashew and other nut shells. To this end, gas and aerosol emissions were quantified for the pyrolysis of maize cobs, sesame stems, grasses, twigs, and coffee husks in a conical soil pit Kon-Tiki flame curtain kiln in Gulu, Northern Uganda, as well as that of maize cobs and coffee husk in a 100 L metal Kon-Tiki container in Masaka, South-West Uganda. The current data are the first ones on non-woody biomasses in flame curtain kilns. They are important for life-cycle analyses (LCAs) of converting various ubiquitous biomasses into biochar using the simple and directly accessible flame curtain technology. Emission measurements are mandatory for a correct LCA of biomass conversion processes [21].

2. Materials and Methods

2.1. Flame Curtain Construction

When a "Kon-Tiki" flame curtain kiln is in operation, a flame is maintained above the pyrolyzing material to catch and combust gases, preventing emissions to the atmosphere. For maize cobs, sesame stems, grass, and twigs, cone-shaped kilns were dug at the premises of Kijani Forestry, Gulu, Northern Uganda, at the end of the dry season in January 2024. A metal 100 L Kon-Tiki was deployed at Masaka, South-West Uganda, for the pyrolysis of maize cobs and coffee husks. The kilns were fed manually by experienced operators at ~2 min intervals to ensure the flame curtain was intact according to the procedure described by Schmidt and Taylor [4] and later refined by Jayakumar, Morrisset [8]. Kiln operation required skilled handling, especially for grass. For example, newly added grass was slightly lifted by poles directly after feeding to avoid quenching the fire curtain. Care was also taken to slowly add sesame stems, maize cobs, and twigs in monolayers, as the alternative of feeding the kiln by adding them too quickly in multiple layers would result in the full combustion of parts of the feedstock above the air–biochar interface.

2.2. Feedstocks, Moisture and Carbon Content

Feedstocks included maize cobs (*Zea mays*), sesame stems (*Sesamum indicum*), elephant grass (*Cenchrus purpureus*), coffee husks (Robusta, *Coffea canephora*), and a 50/50 *w*/*w* mixture of elephant grass and woody twigs from mixed local sources (predominantly *Combretum* wooded grassland with the characteristic species being *Combretum molle* [22]). The sizes of the feedstocks were as follows: maize cobs 15–20 cm in length; sesame stems

30–50 cm in length and 5 mm thick; grass 80–100 cm in length and 2–3 mm thick; twigs 80–100 cm in length and 10–20 mm thick; coffee husk 10 mm diameter. Feedstock moisture was measured with a Protimeter Timbermaster BLD5609 (Amphenol Thermometrics, Taunton, U.K.; 1% accuracy) for maize cobs, sesame stems and twigs and by weight loss at 60 °C in a muffle furnace overnight for grass and coffee husk. Moisture contents were 11.2 ± 2.4% (n = 25) for maize cobs, 9.6 ± 1.5% (n = 12) for twigs, 10.0 ± 1.5% (n = 25) for sesame stems, 8.0 ± 1.0% (n = 3) for grass, and 12.1 ± 1.1% (n = 3) for coffee husk (Table 1). The carbon, hydrogen, and nitrogen contents of the biochars were measured by element analysis after combustion at 1050 °C and chromatographic detection in a Leco 836 element analyzer, LECO Corporation, St. Joseph, MI, USA [7].

Table 1. Moisture contents (%), biomass weight in (kg dry weight, dw), biochar mass out (kg), biochar mass yield (%), feedstock C contents (%), biochar C, H, N contents (%), biochar H/C ratios, biochar pH.

Feedstock	Feedstock Moisture	Biomass In	Biochar Out	Duration	Biochar Mass Yield	Feedstock C	Biochar C	Biochar H	Biochar N	H/C Ratio	Biochar pH
	%	kg dw	kg dw	min	%	%	%	%	%	wt/wt	
Grass	8.0 ± 1.0	60.1	13.0	35	21.7	41.6 [a]	48.8 ± 0.5	2.17 ± 0.04	0.53 ± 0.02	0.04	10.01 ± 0.01
Grass + twigs	9.6 ± 1.5	63.6	14.4	52	22.6	44.5 [b]	67.9 ± 0.3	3.00 ± 0.05	0.77 ± 0.02	0.04	9.84 ± 0.03
Maize cobs	11.2 ± 2.5	19.0	4.8	96	25.2	48.6 [c]	81.6 ± 0.6	2.94 ± 0.05	0.74 ± 0.02	0.04	9.55 ± 0.01
Sesame stems	10.0 ± 1.5	35.2	9.1	33	25.8	44.5 [d]	54.5 ± 0.6	2.48 ± 0.05	1.10 ± 0.03	0.05	9.91 ± 0.02
Coffee husk	12.1 ± 1.1	n.d. [e]	n.d. [e]	10	n.d. [e]	46.3 [f]	n.d. [e]	n.d. [e]	n.d. [e]	n.d. [e]	n.d. [e]
Twigs and leaves (10% moisture) [g]	14.7 ± 3.4	Literature			24.8	47.4 [h]	81.2 ± 1.6	2.62 ± 0.30	n.d.	0.03	n.d.
Twigs with 25% moisture [i]	25.0	Literature			22.0	40.3 [i]	75.4 ± 9.3	1.89 ± 0.46	0.69 ± 0.16	0.03	n.d.

[a] from Braga, Costa [23]. [b] from Braga, Costa [23] and Martin and Thomas [24]. [c] from Sulaiman, Adetifa [25]. [d] from Khairy, Amer [26]. [e] not determined as this feedstock was pyrolyzed during a run with maize cobs, as it proved impossible to pyrolyze pure coffee husk in a flame curtain kiln. [f] from Hidayat, Afriliana [27]. [g] from Cornelissen, Sørmo [19]. [h] from Martin and Thomas [24]. [i] from Cornelissen, Pandit [7].

2.3. Kiln Operation

In all runs, 20 to 70 kg of dry feedstock were used. Coffee husk was pyrolyzed during a 10 min interval within the course of a run with maize cobs. Reported data for maize cobs were based on a run with only maize cobs. Emitted gases were sampled in conical chimneys placed above the Kon-Tiki kilns (for pictures of the hood, see the work of Cornelissen, Sørmo [19]). 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. We reduced the effect of variations in microclimate by conducting the measurements under comparable weather conditions and in the presence of large windshields (Figure S1). Care was taken to use feedstocks that were as homogeneous and uniformly sized as possible. Quenching was performed immediately after the last flames disappeared, with the same amount of water and at the same rapid speed (within a few seconds) for all measurements. Temperatures have earlier been reported to range from 600 °C to 810 °C for Kon-Tiki kilns with dry feedstock [19].

2.4. Emission Measurements

Gases analyzed were CO_2, CO, CH_4, NO_x, and aerosols ("smoke", Total Suspended Particles (TSP), derived from PM_{10}). Instrumentation, carbon mass balance calculations, and statistical analyses were carried out as described in previous work [7,19,28]. As in those works, a Microtector II 6460 (GfG Instrumentation, Ann Arbor, MI, USA) was used to analyze carbon dioxide (CO_2) and methane (CH_4) by infrared sensors and NO by an electrochemical sensor. CO_2 had a detection limit of 0.1%, CH_4 of 0.005% (0.1% of the Lower Explosive Limit of 5%), and NO of 1 ppm (0.0001%). To account for potential emissions related to methane concentrations below the instrument limit of quantification (LOQ), we

assigned a discreet value of LOQ/2 (0.0025%). Data points recorded as <LOQ were hence reported as an EF of <5.5 g kg^{-1} biochar. The instrument converted nitric oxide (NO) to total nitrogen oxides (NO_x) by applying a conversion factor of 1.05, thus assuming 95% of NO_x consists of NO [29]. As with methane, to account for potential emissions related to NO_x concentrations <LOQ, a discreet value of LOQ/2 (0.05 ppm) was assigned. Data points recorded as <LOQ were hence reported as an EF of <0.006 g kg^{-1} biochar.

Carbon monoxide (CO) was analyzed with a Kigaz 300 flue gas analyzer (Kimo Instruments, Le Val-Saint-Germain, France) by internal jacket-type electrochemical sensors, with a detection limit of 1 ppm (0.0001%). For CO values above 8000 ppm, the instrument internally dilutes the gas stream to detect concentrations of up to 50,000 ppm.

Particles in the form of PM_{10} were analyzed with a Thermo Scientific PDR-1500 (Thermo Fisher Scientific, Franklin, MA, USA) instrument with photometric detection of particles (limit of detection 0.1 $\mu g/m^3$).

Non-methane volatile organic carbon (NMVOC) emissions were only measured at a few data points for some feedstocks before sensor failure during fieldwork. NMVOC has earlier been shown to constitute <0.1% of total carbon emitted and <1% of all products of incomplete combustion (all gases except CO_2) [7,19,28]. Therefore, NMVOC data are omitted from this study.

To calculate the emission factors of the kilns, the carbon balance method was utilized [28,30,31]. In this method, only the emission ratios between the gases are measured, without the need to register the absolute mass of gases emitted. Instead, this mass is calculated by performing a carbon balance between the biomass entering the process and the biochar produced. From ten to twenty single-point ratios, time-weighted average values were calculated. Net molar component-to-CO_2 emission ratios for the measured gases and TSP (from PM_{10}) for the flame curtain runs were calculated for CO, CH_4, TSP, and NO_x. These ratios were used to calculate the emission factors in g per kg biochar produced. Two-sample t-tests with unequal variance were used to test for the effects of feedstock type on gas emission factors. Median values and interquartile ranges were reported to avoid data bias due to the high inherent variability of the measurements.

3. Results and Discussion

3.1. Biochar Yields and CH Contents

Biochar yields were 21.7–25.8% d.w. for the various biomass types, similar to the 22–25% previously reported for twigs in Kon-Tiki kilns [7,8,11,19]. C contents were lower for the grass (48.5%) and sesame (54.5%) biochars than for the grass/wood mixture (67.8%) and maize cob ones (81.6%; Table 1). H contents, at 2.5–3.0%, showed less dependence on biomass type (Table 1). H/C ratios were low (0.04–0.05), indicative of relatively high pyrolysis temperatures (>700 °C) [4,19] and high biochar stability [32].

3.2. Gas Emission Factors

Importantly, methane emissions were below quantification levels (i.e., <5.5 g kg^{-1} biochar) for grass, maize cobs, and grass/twigs (Table 2). For sesame stems, methane emissions were detected only during two short positive methane detections of 253 and 1097 g kg^{-1} biochar lasting around 10 to 30 s halfway through the pyrolysis process and during final quenching, respectively. Over the whole pyrolysis cycle, this value would increase the average methane emissions from <5.5 to 17 g kg^{-1} biochar. Delaying quenching by a few minutes might have resulted in complete pyrolysis of the sesame stems at the surface, and this could have avoided the second and highest spike in methane emissions. Low methane emission factors were mostly in accordance with earlier reported values for dry (15% moisture) twigs (0–3.6 g kg^{-1}) and lower than those for twigs with 25% moisture (28.5 g kg^{-1}) [7]. Much higher methane emission factors were measured for coffee husks (179 g kg^{-1}; Table 2) due to the flame curtain being quenched by the smaller particle size of this feedstock. The grass biomass was lifted by poles upon addition to the kiln to avoid disruption of the flame curtain, and through this approach, the pyrolysis of pure grass

biomass was found not to result in detectable methane emissions. Maize cobs also had to be added at a low rate to avoid quenching the flame curtain, highlighting the importance of keeping the flame curtain intact. Methane emissions of 179 g kg^{-1} biochar, as observed in this coffee husk trial, correspond to around 4.5 kg CO_2-eq kg^{-1} biochar (Table 2), exceeding the approximately 2.0–2.5 kg CO_2-eq sequestered by biochar amendment to soil [33]. The data show that many different biomasses can be pyrolyzed with low to zero methane emissions, except for finely grained feedstocks such as coffee husks and likely rice husks and cashew nut shells as well. Furthermore, quenching is a part of the cycle that is especially prone to methane emissions. First, after the last feedstock addition, quenching needs to be delayed until after the flames have disappeared, which is a signal of pyrolysis completion. Second, quenching has to be fast and effective to avoid methane emissions when there is no more flame curtain to combust potential syn-gases from the last stages of the pyrolysis process.

Table 2. Emission factors (g kg^{-1} biochar) of CO_2, CO, CH_4, TSP [aerosols, from particulate matter < 10 µm (PM_{10})], the sum of nitrogen oxides (NO_x), and composite CO_2-equivalents. Median values and interquartile ranges (IQRs—numbers in brackets) per run. Literature values on emissions from Kon-Tiki flame curtain kilns.

Feedstock	*n* [a]	CO_2	CO	CH_4	TSP	NO_x	CO_2-eq. [b]
				g kg^{-1} Biochar			
Grass	17	5122	39 (33–47)	<5.5 [c]	16 (13–24)	0.13 (0.00–0.19)	78
Grass + twigs	19	4576	33 (27–60)	<5.5 [c]	45 (31–72)	<0.006 [d]	66
Maize cobs	21	3933	68 (56–107)	<5.5 [c]	27 (17–40)	0.07 (0.00–0.16)	136
Sesame stems	17	1197	28 (25–41)	17 [e]	14 (12–18)	0.04 (0.00–0.07)	481
Coffee husk	4	2782	n.d. [f]	179 (134–274)	331 (287–356)	<0.006 [d]	4500
Twigs and leaves (10% moisture) [g]	25	3633	101 (60–181)	<5.5 [c]	62 (29–97)	0.01 (0.00–0.03)	202
Twigs (25% moisture) [h]	190	3944	32	28.5	9.3	0.55	777

[a] *n* is the number of emission measurements on which the medians and IQRs were based. [b] based on a 100-year GWP of 25 for methane [16] and 2.0 for CO [17]. CO_2 emissions are excluded here as the CO_2 had originally been taken up by the feedstock biomass. Methane emissions < 5.5 g kg^{-1} biochar are set to zero in this calculation. [c] <5.5 g kg^{-1} biochar when setting measurements at each time point to LOQ/2 (0.0025%). [d] <0.006 g kg^{-1} biochar when setting measurements at each time point to LOQ/2 (0.05 ppm). [e] approximate value based on one spike lasting around 30 s during quenching and averaged over the whole duration of the run (33 min). [f] not determined due to sensor failure. [g] from Cornelissen, Sørmo [19]. [h] from Cornelissen, Pandit [7].

Emission factors for CO (between 21 and 82 g kg^{-1} biochar; Table 2) were close to those previously reported for dry twigs in Kon-Tiki kilns (52 g kg^{-1} [7]; 3–24 g kg^{-1} [8]; 101 g kg^{-1} [19]). CO emissions were higher for maize cobs (70–90 g kg^{-1}) than for grass ($p = 0.02$), sesame stems ($p = 0.0007$), and grass/twigs ($p = 0.04$; all 30–40 g kg^{-1}), probably because the conversion of CO to CO_2 is less efficient for maize cob as a denser feedstock than grass, sesame stems, and sticks, which allow for better mixing between oxygen and the emitted syn-gases. CO emissions were lower than those from traditional kilns (351 g kg^{-1} [28] and retort kilns (148 g kg^{-1} [28]) for all biomass types and comparable to those from Top-Lit Updraft Kilns (TLUDs; 94 g kg^{-1} [28]). CO emission factors could not be quantified for coffee husk pyrolysis due to sensor failure. This led to maximum deviations of <3% in the overall carbon balance (CO being <3% of total gas emissions) and a slight (<3%) uncertainty in the other emission factors reported for this feedstock. In general, the large interquartile ranges in all emission factors do not reflect a lack of data but a high variability of gas emissions during operation, which is caused by variations in burning conditions during individual runs.

NO_x emissions close to detection limits were observed for all biomass types (<0.13 g kg^{-1} biochar; Table 2), probably explained by pyrolysis temperatures (<800 °C [7]) below those needed for the oxidation of ambient N_2 to NO_x (<1000–1200 °C [34]).

Aerosol emissions (TSP; PM_{10}) were in the range of 16–45 g kg^{-1} biochar (Table 2) for all biomass types except coffee husk (331 g kg^{-1} biochar), and significantly lower for grass and sesame stems (<25 g kg^{-1} biochar) than for grass/twigs and maize cobs (>30 g kg^{-1} biochar; sesame vs. grass/twigs, $p = 0.003$; sesame vs. maize, $p = 0.04$; grass/twigs vs. grass, $p = 0.002$; grass vs. maize, $p = 0.02$).

All TSP emissions were slightly above values previously reported for both Kon-Tiki and other kilns (around 10 g kg^{-1} biochar [7]), and in the same range as previously reported values for twigs + leaf litter (62 g kg^{-1} biochar [19]). Aerosol emissions from coffee husk pyrolysis (331 g kg^{-1} biochar) exceeded those for the other biomass types, indicating that aerosol emissions spiked in concert with methane emissions upon unintentional quenching of the flame curtain caused by the addition of this finely grained feedstock. This finding confirms our earlier suggestion that feedstock type, rather than moisture content, is decisive for aerosol emissions from flame curtain kilns [19]. Earlier work showed higher ratios of organic to black carbon in green fuels (19.2 ± 4.2) compared to dry wood logs (7.3 ± 1.9), indicating that more moisture in green biomass resulted in more smouldering-phase combustion and higher aerosol emissions [35]. Further, higher combustion temperatures in wood stove burns led to lower emissions [35]. This result corroborates earlier findings that pyrolysis of the currently studied green wastes resulted in higher aerosol emissions than dry woody twigs [19]. Our study thus confirms that fire intensity plays a role in aerosol emission patterns, with higher aerosol emissions for greener fuel types that burn with lower intensity (the non-woody feedstocks here and field underburns, green leaves, and branches in the work of Zhang, Obrist [35]).

The current data confirmed that Kon-Tiki kilns are not the cleanest kilns when regarding aerosol emissions, as the currently reported emissions factors were higher than those earlier reported for woody feedstocks in traditional kilns, retort kilns, and TLUDs (19, 11, and 7 g kg^{-1}, respectively [28]). Syn-gas combustion, such as in Pyreg and large-scale reactors, further reduces aerosol emissions (0.05–2.5 g kg^{-1} biochar [36,37]).

Properties for the combustion analysis of biomass are usually classified into physical, chemical, and thermal properties [38]. Physical properties include density, porosity, and internal surface area. Twigs and sesame stems create a low density and large porosity at the flame curtain front, allowing for the full combustion of pyrolysis gases. Grass needs to be added with care and lifted at intervals with rakes to provide sufficient porosity (for oxygen penetration). Its advantage is its low density. Dense materials that form nonporous clusters, such as coffee husk, grains, and rice husk, are thus not ideal for maintaining the flame curtain, which is important for effectively combusting the pyrolysis gases. Important chemical properties for combustion are the composition of the biomass and the heating value of the volatiles it produces [38]. The higher lignin content of olive husk (50%) was found to result in a higher biochar yield in comparison with corncob (15% lignin) [39]. Lignin, generally more stable than cellulose or hemicellulose [40], will be completely decomposed at above 500 °C [41]. The lignin contents of grasses are typically 22–25% (of eight grass species studied [42]); of sesame stems, 22% [43]; and of woody materials typical for the Miombo forest biome, 15–16% [44]. Coffee husk contains up to 42% lignin, similar to the 42% lignin found in olive husk [45]. This indicates that a role in the pyrolysis process is played not only by particle size and biomass moisture content but also probably by lignin content, with denser, smaller, wetter, and high-lignin biomasses being the most challenging to pyrolyze with low emissions and high efficiency.

The thermal properties of biomass include specific heat, heat of pyrolysis, and thermal conductivity. The caloric contents of all feedstocks are in the same range of 15 to 20 MJ kg^{-1} [46]. Thus, the caloric content is probably not an important factor causing substantial differences in emissions between feedstocks. The effect of temperature and biomass grain size on biochar yield was also studied in a simple batch pyrolysis reactor [39]. A high temperature (>700 °C, similar to the temperature of a flame curtain kiln [4]) and smaller particles increased the heating rate, resulting in a decreased biochar yield.

Composite CO_2-equivalents were calculated on the basis of methane and CO emissions (Table 2), with a 100-year GWP of 25 for methane [16] and 2.0 for CO [17]. CO_2 emissions are excluded here as the CO_2 was the original source of carbon in the feedstock biomass. Most CO_2-eq. emissions (60–500 g kg^{-1} biochar) were well below the approximately 2000–2500 g kg^{-1} biochar CO_2-eq sequestered by biochar amendment to soil [33]. However, these emissions need to be accounted for when quantifying the number of carbon certificates potentially awarded to farmers for pyrolysis and subsequent soil amendment of the biochar [11,12,19].

3.3. Consequences

This work marks the starting point for a more extensive database of emission factors for various feedstocks pyrolyzed in different kilns, especially artisanal methods such as Kon-Tiki flame curtain kilns. Such a database could provide a reliable inventory for the life-cycle analyses used to estimate the overall climate change impact of biochar production and soil amendment, which are typically used as scientific bases for carbon accreditation. The simple flame curtain kilns offer multiple advantages: (i) gas and aerosol emissions are relatively low compared to those of other low-cost biochar and charcoal production technologies; (ii) construction and operation are easier and more economical compared to more advanced kilns, and thus more suitable for developing country settings; (iii) pyrolysis is much faster (hours) than for most traditional and retort kilns (days). One of the most important results of this study is that the pyrolysis of two important and ubiquitous feedstocks, maize cobs and grass, does not result in higher emissions than that of woody twigs, provided that the biomass is sufficiently dry (<10–15% moisture) and provided that the operators are skilled enough to keep the flame curtain intact during the whole pyrolysis cycle. This notion implies that other ubiquitous coarser materials (larger than 5 cm diameter), such as coconut shells and cacao pods, can be converted into biochar in flame curtain kilns without methane emissions and with low aerosol and CO emissions. Uncertainties remain as to whether emissions are equally low for the pyrolysis of less dry batches of these biomass types (>25% moisture). We consider "fine" materials as those that will form dense layers that restrict gas flow and mixing of pyrolysis gases with oxygen in the flame curtain. The distinction between coarse materials that allow for correct operation and fine materials that disrupt the flame curtain will be more evident as data are collected on a larger variation of biomass feedstocks. From the current dataset and earlier investigations, it appears that fine grain-like materials with an overall diameter under 3–5 cm are not suitable for pyrolysis in flame curtain kilns. Also, the timing of the quenching process needs further investigation so that guidelines can be established for an optimal procedure to avoid methane spikes during the finalization of the pyrolysis process.

Another limitation is the applicability of this work to more temperate regions as well as humid tropical areas, such as rainforests, where different feedstocks and weather conditions prevail. This study is most relevant for sub-Saharan Africa and regions with similar climates and crops. Additionally, there is a challenge in finding suitable pyrolysis technologies for finely grained feedstocks like coffee husks, rice husks, cacao husks, cashew shells, and other nut shells. Gasification with efficient syngas combustion in a heat engine presents a viable solution. However, emission factors for the simplest and most economical systems, such as those produced by Husk Power Systems® (Patna, India; Fort Collins, CO, USA), have yet to be published.

The emission results in the present work demonstrate that certification of biochar made from dry maize, sesame, and grass biomass using low-tech pyrolysis should be encouraged. The fact that dry biomass is essential for a negative carbon balance is, however, an important complication in the humid tropics [19]. However, investment in technological upgrades that allow for the use of excess heat generated from the kilns to dry feedstocks could be possible through carbon credit financing to cover hardware expenses. In addition, soil pit flame curtain kilns should only be used when the soil is relatively dry. If not, much of the heat will be lost through evaporation of soil water, and as a result, the temperature

in the kiln will be below optimal for high-quality biochar and possibly result in increased gas emissions. Despite existing challenges, artisanal biochar production from biomasses with limited or no competing uses could have a significantly positive impact on climate, biodiversity, and smallholder livelihoods.

4. Conclusions

The biomass types investigated in the present study, excluding the fine-grained ones (<2–3 cm), would represent a large opportunity for carbon sequestration upon the identification of a viable mechanism to incentivize biochar production by farmers using residues of maize, cacao, cassava, and similar crops. Flame curtain kilns are not suited for fine-grained feedstock because of the resulting flame quenching and subsequent aerosol and methane emissions. The low emissions of maize cob, grass, and sesame stem pyrolysis in flame curtain kilns documented here are important due to the relevance of these biomass residues in cropping systems in sub-Saharan Africa. In 2018, maize was the second most abundant crop in sub-Saharan Africa (93 million metric tons in 2018 [47]), after cassava (169 million metric tons in 2018 [47]), from which the stems also likely provide the same high-quality feedstock biomass that is similar to sesame stems and twigs, due to their similarity. Grass is abundant and accessible to most farmers in the region. The 33 million smallholder farmers in sub-Saharan Africa could potentially obtain at least 50 million tons of biochar feedstock from their maize cobs, cassava stems, and grass. Annually, this could potentially sequester 70–80 million tons of CO_2-eq and improve 12.5 million ha of farmland (application rate 4 t ha^{-1}) [48].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14219649/s1, Figure S1: The setup of the flame curtain kilns in Gulu, Uganda; Figure S2: The devices deployed to monitor emissions; Figure S3: Using a rake to slightly lift newly added grass to allow enough oxygen access to combust all the syngases; Table S1: Raw data for pyrolysis of maize cobs; Table S2: Raw data for pyrolysis of sesame stems; Table S3: Raw data for pyrolysis of grass; Table S4: Raw data for pyrolysis of grass/twigs; Table S5: Raw data for pyrolysis of coffee husk.

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