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Methane Emissions From Flame Curtain Pyrolysis (Kon-Tiki)

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ABSTRACT

Pyrogenic carbon capture and storage is increasingly recognized as a scalable carbon dioxide removal strategy. Flame curtain pyrolysis (Kon-Tiki) enables decentralized biochar production, but its net climate benefit depends on the magnitude of methane emissions caused during production. Here, we compared emissions from flame curtain pyrolysis and open burning of crop residues, which is considered the baseline scenario in many cases. We tested five feedstocks across a range of moisture contents and continuously measured temperature and concentrations of CO_2, CO, CH_4, and C_3H_8 in the flue gas. Emission factors were calculated via carbon mass balance, and regression analysis was used to identify drivers of the variability of methane concentrations. Kon-Tiki pyrolysis resulted in lower CO and CH_4 emissions than open burning, particularly for wheat straw. Dry feedstocks ($\leq 15\%$ moisture) yielded low methane emissions ($< 5\,g\,kg^{-1}$ biochar), whereas moist feedstocks ($\geq 25\%$ moisture) produced up to tenfold higher emissions. Kon-Tiki methane emissions were best explained by flue gas temperatures, showing an exponential decline of methane emissions with increasing temperatures. Overall, replacing open burning with Kon-Tiki pyrolysis is a promising strategy to foster biochar production and reduce greenhouse gas emissions. Nevertheless, managing feedstock moisture and maintaining high temperatures are critical to minimize methane emissions and to enable Kon-Tiki kilns to serve as an effective transitional technology for decentralized biochar production and carbon dioxide removal.

1 | Introduction

Climate change mitigation requires not only rapid and substantial reductions in greenhouse gas (GHG) emissions but also carbon dioxide removal (CDR) from the atmosphere (IPCC 2022). Among the available CDR pathways, pyrogenic carbon capture and storage (PyCCS) stands out due to its high technological readiness and scalability (Schmidt et al. 2019; Smith et al. 2024). This pathway harnesses the ability of plants to photosynthesize atmospheric CO_2 into biomass and thermochemically converts biomass into biochar, a highly stable solid form that can serve as a long-term carbon sink. To function as such, the biochar must be applied to matrices such as soils or materials that prevent rapid oxidation (Schmidt et al. 2019). Consequently, biochar carbon credit certification bodies require mixing biochar with a matrix to certify carbon removal (e.g., CSI 2024; Isometric 2025; Puro.earth 2025). Biochar's persistence in soils has been widely studied, and evidence suggests that large portions of biochar can withstand decomposition on a centennial to millennial timescale (Lehmann et al. 2024; Budai et al. 2016; Schmidt et al. 2025; Woolf et al. 2021).

Technological approaches for biochar production range from large-scale industrial pyrolysis plants to small-scale, artisan systems such as the Kon-Tiki kiln (Schmidt and Taylor 2014). The Kon-Tiki kiln is an affordable tool for decentralized artisanal biochar production. It accommodates a wide range of feedstocks and facilitates the production of biochars and carbon sink credits in voluntary carbon markets (CSI 2024). Its operating principle is the so-called flame curtain pyrolysis. It involves starting a top-lit fire at the bottom of the kiln to produce embers, the burning embers are then spread to form a first layer on the bottom of the kiln. A thin layer of biomass is added on top, which starts outgassing. The rising pyrolysis gas is combusted in the pre-existing flames above the feedstock layer. Subsequently, further layers of bulky biomass are continuously added. The resulting combustion zone (i.e., the flame curtain) consumes available oxygen, which protects the underlying char from oxidation. Pyrolysis gases pass through this flame curtain and are largely oxidized to CO_2 and H_2O, reducing emissions of particulate matter (PM), carbon monoxide (CO), and methane (CH_4) (Cornelissen et al. 2023, 2016; CSI 2024).

Understanding methane emissions of Kon-Tiki pyrolysis is particularly important in this context. Methane (CH_4) is a co-product of biomass pyrolysis and combustion processes. Although it is highly combustible, and therefore readily oxidized in the flame curtain of the Kon-Tiki or in the flames of open combustion events (e.g., wildfires, crop-residue burning), incomplete combustion generally occurs to some extent, leading to methane emissions. In consequence, anthropogenic biomass burning accounts for around 6% of global anthropogenic methane emissions (Jackson et al. 2020). Literature reports a wide range of emission factors for both Kon-Tiki pyrolysis and open burning, particularly on CO and CH_4 emissions (Arai et al. 2015; Cornelissen et al. 2023, 2016; Koppmann et al. 2005). While it was shown that the magnitude of methane emissions depends on the feedstock moisture content (Cornelissen et al. 2023; Hayashi et al. 2014), threshold values for moisture content and the influence of other feedstock characteristics, such as the calorific value, were not systematically investigated.

Methane is a potent greenhouse gas, with a global warming potential 80–86 times that of CO_2 over 20 years and 27 times over 100 years (Forster et al. 2021). Although its atmospheric lifetime is relatively short (12.4 ± 1.4 years, Myhre et al. 2013), CH_4 is responsible for approximately 25% of anthropogenic global warming (Etminan et al. 2016). Minimizing methane emissions from biochar production systems, such as the Kon-Tiki, is thus crucial for their net climate benefit as a carbon sink.

To accurately evaluate the carbon sink potential of biochar, it is essential to compare its production against an appropriate baseline scenario. Biochar production can replace the open-field burning of crop residues, a widespread practice associated with substantial GHG emissions and air pollution (Estrellan and Iino 2010; Gadde et al. 2009; Arai et al. 2015; Akagi et al. 2011; Christian et al. 2003; Hayashi et al. 2014; Stockwell et al. 2014; Li et al. 2007). Despite growing interest in biochar production as an alternative to open burning, a direct comparison of emissions between both approaches has not yet been conducted.

To address this gap, we conducted a side-by-side assessment of emissions from open burning and Kon-Tiki pyrolysis under identical conditions applying consistent measurement methods to ensure comparability. We monitored emissions and flue gas temperatures across a range of feedstocks. Our specific objectives are to: (1) compare emission factors of CO_2, CO, CH_4, and C_3H_8 between open burning and Kon-Tiki pyrolysis of crop residues under controlled conditions; (2) quantify the effects of feedstock type, moisture content, and gas temperature on methane emissions; (3) establish robust emission factors. Based on our findings, we provide recommendations about minimizing greenhouse gas emissions when using flame curtain pyrolysis systems like the Kon-Tiki.

2 | Materials and Methods

2.1 | Feedstock Processing

Dry wheat straw (*Triticum aestivum* L., 10% moisture content) was sourced from farmers (Lleida, Spain). For the runs with semi-moist and moist wheat straw, the feedstock was spread in a thin layer on a tarpaulin and moistened homogenously with a hose and sprinkler applying a predetermined amount of well water. It was covered to facilitate soaking. After 24 h, it was uncovered and left to evaporate excess moisture on the outside of the straws. Before grab-sampling three samples per run for subsequent moisture content analysis (cf. Section 2.5), the feedstock was mixed thoroughly and then used immediately for pyrolysis or open burning tests.

Orchard pruning (*Prunus* spp. L.) and giant reed (*Arundo donax* L.) were collected shortly after pruning activities at a local farm (January 2025, Raimat, Lleida, Spain) and sun-dried to reach one of the three target moisture classes (dry, semi-moist, moist, Table 1), with the moisture content monitored periodically. Feedstocks were covered with tarpaulins to prevent further changes in moisture content during moisture content analysis (cf. Section 2.5) and were then pyrolyzed or burned within 48 h of the sampling. Immediately before

TABLE 1 | Overview of feedstocks and moisture contents tested. Three repetitions of flame curtain pyrolysis were performed per feedstock and moisture category ($n = 3$). For open burning three repetitions were performed in all cases except for moist orchard pruning ($n = 1$).

		Water content [%]			
ID	**Feedstock**	**Dry**	**Semi-moist**	**Moist**	**Open Burning**
C	Coffee (*Coffea arabica*)	14.7		25.7	No
G	Guadua (*Guadua angustifolia*)	11.9		26.9	No
O	Orchard Pruning (*Prunus* spp.)	9.6	19.9	24.7	Yes
R	Giant Reed (*Arundo donax*)		15.9	39.0	Yes, only moist
S	Wheat Straw (*Triticum aestivum*)	10.1	18.1	26.0	Yes

combustion or pyrolysis, three samples were taken to reconfirm the moisture content.

Coffee stem wood (*Coffea arabica* L.) and Guadua (*Guadua angustifolia* Kunth) were obtained from local farmers (Pitalito, Huila and Zipacón, Cundinamarca, Colombia), cut and stored 12 months under a roof (dry) or 2 months outdoors (moist) prior to pyrolysis. Three samples for moisture content analysis were taken immediately before pyrolysis of each run.

2.2 | Flame Curtain Pyrolysis

For this study, metal Kon-Tiki kilns were used (Schmidt and Taylor 2014, Figure 1). A 150 L kiln was employed for all feedstocks, except *Coffea arabica* and *Guadua angustifolia*, which were processed in a 1000 L kiln. A hood with a chimney was installed above the kiln to enable gas emission measurements (Figure 1, Figure S1). Emissions were recorded for three replicates per feedstock and moisture category (Table 1).

We followed Kon-Tiki operation guidelines closely to minimize variability due to operator technique and maximize comparability between replicates. Quenching was conducted with well water. For the 150 L kiln, water was introduced through a hose connected to the bottom. For the 1000 L kiln, water was poured inside from above (carefully along the walls) once visible ash formation began on the uppermost layer after the biomass was used up.

2.3 | Open Burning of Crop Residues

For the open burning tests, an equal mass of feedstock as was pyrolyzed in the Kon-Tiki (dry weight basis, Table S2), was piled loosely under a hood with a chimney and ignited at one spot from the bottom using a wood wool fire starter cube (favorit Öko Zündwolle, Alschu GmbH, Westheim, Germany). Three replications were carried out per moisture category per feedstock type. For the semi-moist giant reed, no open burning runs could be performed due to excessive heat development. For the

FIGURE 1 | Kon-Tiki kilns with 150 L (top left) and 1000 L (top-right) with hood and chimney to collect and channel flue gas emissions to the analyzer probe. Open burning of orchard pruning (bottom), directly after ignition (left) and towards complete combustion (right). A sketch with dimensions of Kon-Tikis, fire place, and hood is shown in Figure S1.

moist fruit orchard pruning, only one run was carried out due to limited availability of feedstock material (Table 1). As only one open-burning replicate was available for moist fruit orchard pruning ($n=1$), no pairwise statistical comparison between open burning and pyrolysis was conducted for this feedstock-moisture category.

2.4 | Gas Emission Measurement

Concentrations of O_2, CO_2, CO, CH_4, and C_3H_8 were continuously measured in the flue gas stream throughout each pyrolysis and open burning test using an MGAprime analyzer (MRU GmbH, Neckarsulm, Germany). The device is equipped with non-dispersive infrared (NDIR) sensors for CO_2, CO, CH_4, and C_3H_8 as well as a paramagnetic O_2 sensor and was calibrated by Kull Instruments (Reiden, Switzerland) to the expected gas concentration ranges. Emission data were recorded at five-second intervals. The sampling probe was inserted horizontally into the center of the exhaust gas stream in the chimney, approximately 1.5 m above the Kon-Tiki kiln or the open burning pile (Figure S1). Gas temperatures were measured with Type K thermocouple integrated in the sampling probe. Sensors were zeroed and the probe cleaned at the start of each measurement day, that is, after 2–3 measurements.

2.5 | Moisture and Laboratory Analysis

Per test run (of pyrolysis or open burning), three feedstock samples were oven-dried for 48 h at 105°C or analyzed with a moisture analyzer (PCE MA 110 TS, PCE GmbH, Meschede, Germany) used in auto-drying mode with infrared heating. Potential deviations in moisture content between moisture analyzer and drying oven method were assessed and found to be minimal (< 2%, Table S1). Moisture content of quenched biochar was determined similarly via drying in an oven or the moisture analyzer. Carbon contents of both feedstock and resulting char were analyzed at a commercial lab (Eurofins Umwelt Ost GmbH, Bobritzsch-Hilbersdorf, Germany) with a CHN elemental analyzer according to DIN 51732 2014, as suggested in the EBC analytical guidelines (EBC 2012–2015; Bachmann et al. 2016). Lower heating values of the feedstocks were analyzed at Eurofins Umwelt Ost GmbH (according to DIN EN ISO 18125 2017). The full dataset is openly available (Ithaka Institute for Carbon Strategies 2026).

2.6 | Carbon Mass Balance Method

The carbon mass balance method is commonly used to calculate emission factors for thermal conversions (Ward and Radke 1993; McMeeking et al. 2009; Cornelissen et al. 2016, 2023; Ward 1979). Here we applied the carbon mass balance method, assessing the ratios of CO_2, CO, CH_4, and C_3H_8 during the combustion processes to calculate the mass of the specific gases and subsequently the emission factors. The feedstock dry weight and its carbon content were quantified to account for the carbon input. Likewise, the absolute biochar or ash (for open biomass burning) dry weight and their carbon content were assessed to account for the carbon output. The balance, subtracting the carbon output from the carbon input, is referred to as carbon loss, occurring in the form of carbonaceous gases and total suspended particles. Here we, measured only the most common carbonaceous flue gases (CO_2, CO, CH_4 and C_3H_8). All other carbonaceous flue gas compounds, for example, suspended particles, were neglected as it has been shown that they only account for less than 2% of the carbon emitted (McMeeking et al. 2009; Andreae and Merlet 2001; Sillanpää et al. 2005; Freeborn et al. 2008). This might lead to a slight overestimation of emission factors for CO_2, CO, CH_4, and C_3H_8 in the range of 1%–2% (McMeeking et al. 2009), as all other carbonaceous compounds are assumed to be zero in the flue gases assessment. The detailed calculation of carbon mass balance was already described in detail elsewhere (Ward and Radke 1993; Cornelissen et al. 2016).

2.7 | Calculations

Modified combustion efficiency (MCE) was calculated as ratio of CO_2 to the sum of CO_2 and CO on a molar basis (Koppmann et al. 2005; Ward and Radke 1993):

$$\text{MCE}\,[\%] = \frac{\text{CO}_2[\text{mol}\,\%]}{\text{CO}_2[\text{mol}\,\%] + \text{CO}[\text{mol}\,\%]} \times 100$$

The lower heating value (LHV) describes the amount of usable heat energy released during complete combustion of a fuel without latent heat recovered by condensation of water vapor. In this study, LHV on a wet basis (LHV_{wb}) was used. It reflects the energy content of the feedstock as processed (i.e., including moisture), accounting for the energy required to evaporate the contained water during combustion. It was used as a quantitative descriptor of the feedstocks and calculated via the formula (Francescato et al. 2008).

$$\text{LHV}_{\text{wb}}\left[\text{MJ kg}^{-1}\right] = \text{LHV}\left[\text{MJ kg}^{-1}\right] \times (1 - W) - 2.441\left[\text{MJ kg}^{-1}\right] \times W$$

With W being the water content of the feedstock and 2.441 MJ kg^{-1} being the latent heat of water evaporation.

Biochar yield (y_{BC}) was calculated with the formula:

$$y_{BC}[\%] = \frac{\text{BM}\,[\text{kg}]}{\text{BC}\,[\text{kg}]}$$

With the biomass dry weight (BM) and the biochar dry weight (BC).

Carbon yield (y_c) was calculated as:

$$y_c[\%] = y_{\text{BC}}[\%] \times \frac{C_{\text{BM}}[\%]}{C_{\text{BC}}\,[\%]}$$

With the carbon content of the biomass (C_{BM}) and the biochar (C_{BC}).

Emission factors are reported in g per kg dry feedstock to enable direct comparison between open burning and Kon-Tiki pyrolysis. In addition, for comparability with the earlier studies on Kon-Tiki emissions (e.g., Cornelissen et al. 2016, 2023, 2024) and values used in certification standards (e.g., CSI 2024), emission factors for Kon-Tiki runs are also reported per kg biochar.

2.8 | Data Analysis

Data analysis was carried out in R (R Core Team 2024) and RStudio (RStudio Team 2020). Statistically significant differences in MCE and emission factors between open burning and flame curtain pyrolysis (Kon-Tiki) were assessed using Welch's unequal variance t-test for pairwise comparisons within each feedstock-moisture class. For moist fruit orchard pruning, no within-class statistical comparison was performed because only one open burning replicate was available ($n = 1$). Overall means across all feedstocks and moisture classes were compared with Welch's t-test when the assumption of normality was met; otherwise, the non-parametric Wilcoxon rank sum test was applied. Additionally, a paired Wilcoxon signed-rank test was used to compare emission factors. Moist orchard pruning runs were excluded from this analysis to ensure a fully paired dataset. For Kon-Tiki pyrolysis, differences among moisture categories (dry, semi-moist, moist) were evaluated using one-way ANOVA when assumptions on normality and homogeneity of variance were met. Welch's ANOVA was used in cases of heteroscedasticity, and the Kruskal–Wallis test with Bonferroni-adjusted p-values was applied when normality assumptions were violated. Post hoc comparisons were performed using Tukey's HSD for one-way ANOVA and the Games-Howell test for Welch's ANOVA. Methane emission factors across feedstock moisture classes were compared with the Kruskal–Wallis test with Bonferroni correction when ANOVA assumptions were not met. Significant differences are assumed at $p < 0.05$ for all tests and are indicated by different lowercase letters. Normality was assessed using the Shapiro–Wilk test (Shapiro and Wilk 1965), and homogeneity of variance was evaluated with Levene's test (Levene 1960) in all cases.

Three models were developed to investigate drivers influencing methane emission factors. Linear regressions were fitted to the square-root-transformed response for feedstock moisture content and LHV_{wb}. Residuals were checked for normality and homoscedasticity, and predictions were back-transformed to the original scale. Model selection was based on Akaike Information Criterion (AIC) and analysis of variance (ANOVA); model fit was quantified using R^2. An exponential nonlinear least squares (NLS) model was found to describe the effect of gas temperatures on methane emission factors best, based on the AIC. Although residuals were not perfectly normal, NLS provides consistent estimates of the mean response. Robust confidence intervals were obtained via bootstrapping ($n = 1000$). The best model fit (based on AIC and ANOVA) to describe the relationship between methane (CH_4) and carbon monoxide (CO) concentrations was found to be a log–log linear regression. Predictions and 95% confidence intervals were obtained on the log scale and back-transformed to the original CH_4 scale for interpretation.

The combined influence of the parameters on CH_4 emissions was evaluated in a multiple linear regression model fitted for Kon-Tiki runs using moisture content (M in %), mean flue gas temperature (T in °C), and effective lower heating value on a wet basis (LHV_{wb} in MJ kg^{-1}) as predictors. The model structure was:

$$\sqrt{CH_4} = \beta_0 + \beta_1 \times M + \beta_2 \times T + \beta_3 \times LHV_{wb} + \varepsilon.$$

Relative predictor importance was assessed by partitioning the explained variance using the Lindeman–Merenda–Gold (lmg) method. Multicollinearity among predictors was evaluated using variance inflation factors (VIF).

3 | Results

Biochar yields in Kon-Tiki kilns ranged from 14% to 29%, and carbon yields from 20% to 43%, with significantly higher yields observed for dry feedstocks compared to moist feedstocks (Figure 2, Table 2, Figure S2). Carbon contents in the biochar were lowest for wheat straw (61%–67%), followed by giant reed (68%–72%), guadua (73%–76%), orchard pruning (79%–84%), and coffee stem wood (79%–87%, Table S2). Feedstock consumption rates ranged from 0.14 kg min^{-1} (wet guadua) to 1.27 kg min^{-1} (dry coffee stem wood). Consumption rate showed a significant negative correlation with moisture content (Spearman's $\rho = -0.67$), with wetter biomass exhibiting lower consumption rates. In our setup, pyrolysis runs were relatively short (25–230 min, mean of 62 min), and feedstock consumption rates might vary for larger Kon-Tiki and larger amounts of feedstock pyrolyzed per run.

CO_2 dominated carbonaceous gas emissions in flame curtain pyrolysis (87.9–99.3 mol%, mean: 95.1% ± 3.6%), while CO ranged from 0.7 to 9.7 mol% (mean: 4.2% ± 3.0%), CH_4 from 0.02 to 2.0 mol% (mean: 0.6% ± 0.6%), and C_3H_8 from 0.01 to 0.35 mol% (mean: 0.12% ± 0.1%) (Figure 2).

In open burning, CO_2 also dominated carbonaceous gas emissions (85.2–98.6 mol%, mean: 93.0% ± 4.6%), while CO ranged from 1.4 to 12.2 mol% (mean: 6.0% ± 3.7%), CH_4 from 0.01 to

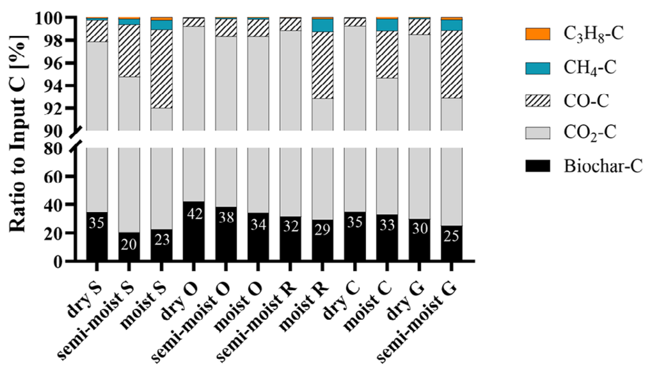

FIGURE 2 | Relative share of biochar-C (carbon yield) and carbonaceous flue gases measured (CO_2, CO, CH_4, C_3H_8) of input (i.e., feedstock) carbon for various feedstocks (S = Wheat straw, O = Orchard pruning, R = Giant Reed, C = Coffee stem wood, G = Guadua bamboo) and feedstock moisture contents ("dry" ≤ 15%; "semi-moist": 16%–24%, "moist" ≥ 25%). For each combination of feedstock and moisture content 3 measurements were carried out ($n = 3$) and the mean is shown here. Error bars are omitted to improve visual clarity; individual data points are provided in the Table S2.

TABLE 2 | Comparison of emission factors for flame curtain pyrolysis of various feedstocks (S = Wheat straw, O = Orchard pruning, *R* = Giant reed, C = Coffee stem wood, G = Guadua bamboo) and moisture contents.

	Water cont.	LHV_{wb}	MCE	Emission factors per feedstock mass (dw)				Emission factors per biochar mass (dw)				Mean gas temp.	Biochar yield
Feedstock	[%]	[MJ kg^{-1}]	[%]	CO_2 [kg kg^{-1}]	CO [g kg^{-1}]	CH_4 [g kg^{-1}]	C_3H_8 [g kg^{-1}]	CO_2 [kg kg^{-1}]	CO [g kg^{-1}]	CH_4 [g kg^{-1}]	C_3H_8 [g kg^{-1}]	[°C]	[%]
S dry	10	15.2	97.1 ± 0.4	1.1 ± 0.1	20 ± 4	1.1 ± 0.2	0.3 ± 0.0	4.5 ± 1.3	87 ± 26	4.8 ± 1.7	1.4 ± 0.3	168 ± 16	24 ± 5
S semi-moist	18	13.6	94.2 ± 0.8	1.2 ± 0.0	49 ± 7	2.9 ± 0.4	0.7 ± 0.2	8.6 ± 0.3	341 ± 59	20.0 ± 2.9	5.1 ± 1.3	126 ± 17	14 ± 0
S moist	26	12.1	91.0 ± 0.9	1.2 ± 0.0	73 ± 8	5.2 ± 0.6	1.4 ± 0.2	6.9 ± 0.6	437 ± 80	30.8 ± 5.7	8.4 ± 1.6	96 ± 11	17 ± 1
O dry	10	17.4	98.7 ± 0.6	1.0 ± 0.0	8 ± 4	0.4 ± 0.2	0.1 ± 0.1	4.1 ± 0.1	34 ± 17	1.7 ± 0.9	0.4 ± 0.3	216 ± 25	25 ± 0
O semi-moist	20	15.1	97.5 ± 0.3	1.1 ± 0.0	18 ± 2	0.8 ± 0.2	0.2 ± 0.0	4.7 ± 0.1	77 ± 8	3.4 ± 0.7	0.8 ± 0.0	152 ± 8	23 ± 0
O moist	25	14.1	97.7 ± 1.3	1.2 ± 0.0	17 ± 9	1.0 ± 0.7	0.2 ± 0.1	5.5 ± 0.4	82 ± 43	4.6 ± 3.2	0.8 ± 0.4	201 ± 46	21 ± 1
R semi-moist	16	14.9	98.4 ± 0.8	1.2 ± 0.1	12 ± 6	0.3 ± 0.2	0.1 ± 0.0	5.7 ± 0.7	60 ± 35	1.4 ± 1.1	0.5 ± 0.2	143 ± 9	21 ± 2
R moist	39	10.2	91.5 ± 1.2	1.1 ± 0.0	65 ± 8	6.9 ± 2.2	0.9 ± 0.2	5.4 ± 0.3	320 ± 33	33.7 ± 9.9	4.2 ± 1.0	93 ± 6	20 ± 0
C dry	15	15.2	98.9 ± 0.2	1.2 ± 0.0	8 ± 1	0.3 ± 0.2	0.1 ± 0.0	5.8 ± 0.2	40 ± 8	1.6 ± 1.0	0.7 ± 0.2	232 ± 28	20 ± 0
C moist	26	14.1	93.7 ± 0.5	1.1 ± 0.0	49 ± 4	7.0 ± 0.5	0.7 ± 0.2	5.9 ± 0.3	255 ± 17	36.8 ± 3.6	3.9 ± 0.9	126 ± 36	19 ± 1
G dry	12	15.7	98.1 ± 0.2	1.2 ± 0.0	15 ± 2	0.7 ± 0.1	0.2 ± 0.0	6.4 ± 0.6	80 ± 13	3.5 ± 0.9	1.1 ± 0.1	199 ± 10	19 ± 1
G moist	27	12.6	91.9 ± 0.5	1.2 ± 0.0	67 ± 3	6.3 ± 0.9	1.1 ± 0.1	7.2 ± 0.8	402 ± 25	37.8 ± 8.7	6.7 ± 0.9	77 ± 4	17 ± 1
Mean dry	11.6 ± 2.1 c	15.9 ± 1.0 a	98.2 ± 0.8 a	1.2 ± 0.1 a	13 ± 6 b	0.6 ± 0.4 b	0.2 ± 0.1 b	5.2 ± 1.1 a	60 ± 29 b	2.9 ± 1.7 b	0.9 ± 0.5 b	204 ± 30 a	22.0 ± 3.2 a
Mean semi-moist	17.9 ± 1.7 b	14.6 ± 0.8 b	96.7 ± 2.0 a	1.2 ± 0.1 a	26 ± 18 b	1.3 ± 1.2 b	0.3 ± 0.3 b	6.3 ± 1.8 a	159 ± 141 ab	8.3 ± 9 b	2.1 ± 2.3 b	140 ± 15 b	19.4 ± 3.9 ab
Mean moist	28.4 ± 5.5 a	12.6 ± 1.6 c	93.1 ± 2.6 b	1.1 ± 0.0 a	54 ± 22a	5.3 ± 2.5 a	0.9 ± 0.4 a	6.2 ± 0.9 a	299 ± 136 a	28.7 ± 14 a	4.8 ± 2.8 a	119 ± 51 b	18.9 ± 2 b

Note: MCE refers to the modified combustion efficiency. LHV_{wb} to the lower heating value, corrected for the respective moisture content, that is, the usable energy content of the moist feedstock. Emission factors are presented in g per kg feedstock and per kg of biochar produced (both on a dry weight basis - dw). Values are presented as mean ± standard deviation ($n = 3$). Statistically significant differences among feedstock moisture categories (dry, semi-moist, moist) are represented by different lowercase letters and based on one-factorial ANOVA, Welch's ANOVA, or Kruskal-Wallis test, when assumptions were violated.

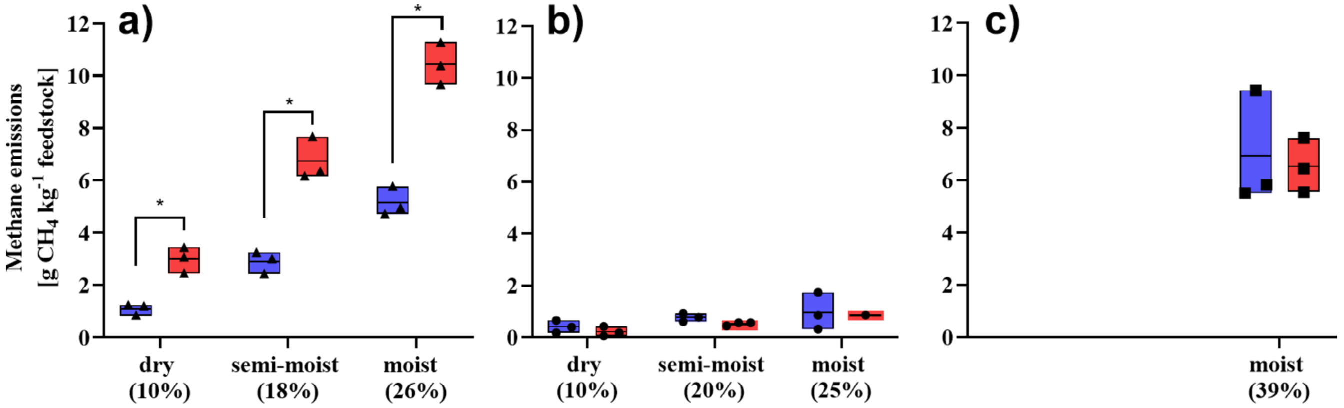

FIGURE 3 | Methane emission factors [g CH4 kg^{-1} feedstock] for flame curtain pyrolysis (blue) and open biomass burning (red), for (a) wheat straw, (b) orchard pruning, (c) giant reed at different moisture content levels. Bars range from min to max, horizontal line represents the arithmetic mean. Black dots represent datapoints, $n=3$, except open burning of moist orchard pruning ($n=1$), where the red line serves merely as visual aid. Statistically significant differences between open burning and Kon-Tiki emissions were assessed with Welch's *t*-tests ($p<0.05$) and are represented with an asterisk (*).

2.0 mol% (mean: 0.8% ± 0.7%), and C_3H_8 from 0.01 to 0.5 mol% (mean: 0.21% ± 0.18%). However, the mean share of CO_2 on all carbonaceous gases measured was higher for the Kon-Tiki than open burning, also resulting in a tendentially higher modified combustion efficiency (MCE) for pyrolysis (95.4% ± 3.1%) compared to open burning (93.9% ± 3.8%). The lowest MCE (88.1% ± 1.0%) was recorded for open burning of wet straw, while all pyrolysis runs showed MCEs above 90%.

Emission factors for flame curtain pyrolysis and open burning are expressed in g emitted gas per kg of feedstock (g kg^{-1} FS, dry weight) to allow for comparison among both. On average, emission factors of flame curtain pyrolysis were lower than for open burning for CO_2, CO, CH_4, and C_3H_8 (Table S3). Mean CO emissions ranged from 8 to 73 g kg^{-1} FS for flame curtain pyrolysis (mean: 36 ± 26 g CO kg^{-1} FS) and from 13 to 115 g kg^{-1} FS for open-burning (mean: 59 ± 38 g CO kg^{-1} FS, Table S3). For the same feedstock type and moisture content, CO emissions from flame curtain pyrolysis were consistently lower than those from the corresponding open-burning events (Table S3). Mean CH_4 emissions ranged from 0.4 to 6.9 g kg^{-1} FS for flame curtain pyrolysis (mean: 2.6 ± 2.5 g CH_4 kg^{-1} FS) and from 0.2 to 10.4 g kg^{-1} FS for open-burning events (mean: 4.4 ± 3.8 g CH_4 kg^{-1} FS). Methane emissions from open burning significantly exceeded flame curtain pyrolysis emissions for wheat straw ($p<0.001$, $r=0.93$), but not for orchard pruning ($p=0.18$, $r=-0.35$) and giant reed ($p=0.65$, $r=-0.35$, Figure 3).

Compared to straw, lower emission factors were observed for orchard pruning across all moisture categories. For the latter, no significant difference between emissions from pyrolysis and open burning was observed (Figure 2b). Mean methane emission factors were low (≤ 1 g kg^{-1} FS) for woody feedstocks in both flame curtain pyrolysis and open burning. Overall, CO emissions decreased by an average of 35% (−19 g kg^{-1} FS), while CH_4 emissions dropped by 36% (−1.4 g kg^{-1} FS) in the flame curtain pyrolysis compared to open burning. When comparing flame curtain pyrolysis and open burning across all feedstocks and moisture levels, using a paired Wilcoxon signed-rank test, significantly lower emission factors for CO ($p<0.001$, $r=-0.87$) and CH_4 ($p<0.05$, $r=-0.52$) were observed.

Assessing emission factors for flame curtain pyrolysis, we found that feedstock type and moisture content influenced emissions. Across all feedstocks, dry feedstocks (≤ 15% moisture content) had significantly higher MCEs (98.2%), lower CO (60 g kg^{-1} biochar), and lower CH_4 (2.9 g kg^{-1} biochar) emissions than moist (≥ 25%) feedstocks. A Spearman's rank correlation coefficient of $\rho=0.72$ is evidence of a strong relationship between feedstock moisture and methane emission. Moist feedstocks emitted on average nearly ten times more CH_4 (2.9 versus 28.7 g kg^{-1} biochar) compared to dry feedstocks (≤ 15%) and also showed the lowest average MCE (93.1%) and biochar yields (18.9%, Table 2). All dry feedstocks (≤ 15% moisture) showed mean emission factors < 5 g CH_4 kg^{-1} biochar (Table 2).

The feedstock type also impacted methane emission factors. For orchard pruning, methane emission factors remained low through all moisture categories (Table 2). For wheat straw, increasing moisture content from 10% to 26% led to a more than fivefold increase in CO and CH_4 (Table 2). Similar trends were observed in other feedstocks, with the most pronounced increases in CO and CH_4 emissions seen in moist giant reed and coffee stem wood, with 1.6 and 36.8 g CH_4 kg^{-1} for dry and moist coffee stem wood, respectively.

Mean gas temperatures were significantly higher for dry feedstocks (204°C ± 30°C) than for moist feedstocks (119°C ± 51°C, Table 2). A negative exponential model with mean gas temperature as predictor ($R^2=0.74$; Figure 4c), where methane emissions decrease substantially with increasing gas temperatures, provided a better fit compared to the quadratic regression models with feedstock moisture content and LHV_{wb} (Figure 4). In short, exhaust gas temperature above the Kon-Tiki was the best fitting predictor for methane emissions irrespective of the feedstock type.

To assess the relative importance of moisture content, flue gas temperature, and LHVwb in determining CH_4 emissions, a combined multiple regression model was fitted ($R^2=0.75$; adjusted $R^2=0.73$; $p<0.001$). Variance partitioning (lmg) indicated

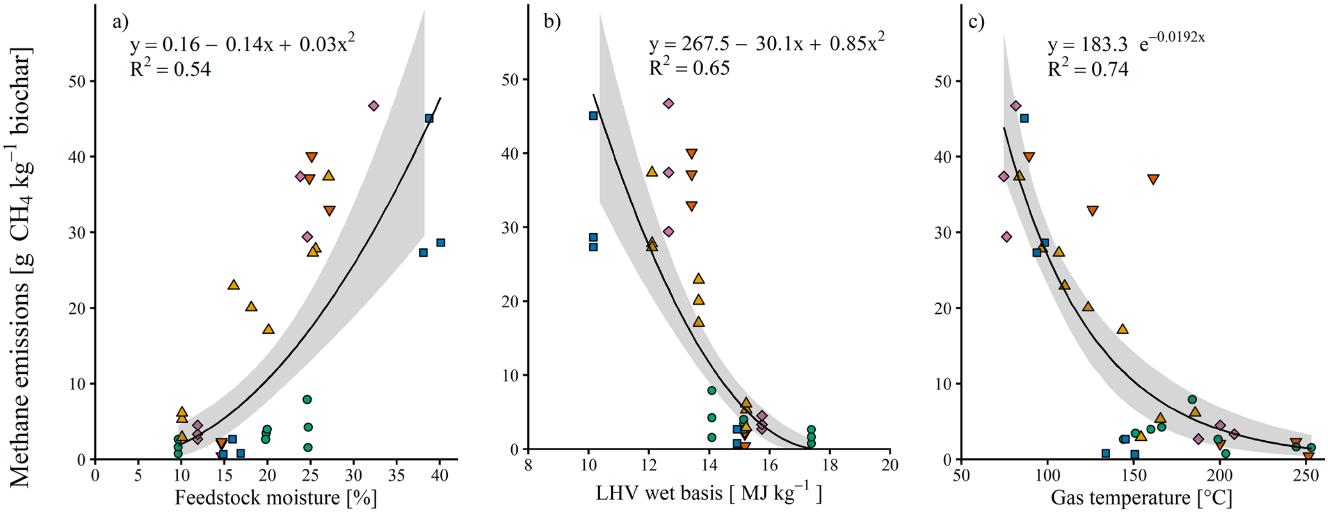

FIGURE 4 | Impact of feedstock moisture content (a), lower heating value on a wet basis, representing the usable energy content of the moist feedstock (b), and flue gas temperature on flame curtain pyrolysis methane emission factors (g CH_4 kg^{-1} biochar). Feedstocks are depicted with varying symbols as data points: wheat straw: yellow triangles; orchard pruning: green dots, guadua: pink rhombs, coffee: orange down-pointing triangles; giant reed: blue squares. Black lines represent the model prediction; the gray band represents the confidence interval (95%).

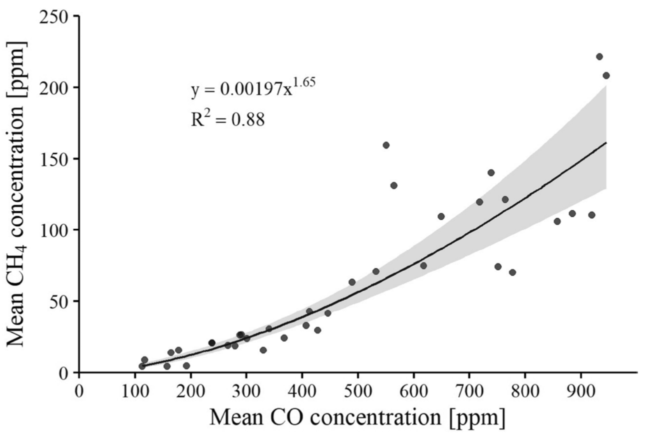

FIGURE 5 | Relationship between methane (CH_4) and carbonmonoxide (CO) in the flue gas. Curve was fitted with a linear model: Log $(CH_4) = a + b \log(CO)$ and then transformed to the original scale. The black line represents the function: $CH_4[ppm] = 0.00197 * CO[ppm]^{1.65}$. The gray area represents the 95% confidence interval.

that flue gas temperature accounted for 39% of the explained variance, followed by LHV (35%) and moisture content (27%). However, predictors were partially collinear (VIF up to 8.6), reflecting the strong (physical) coupling between moisture, energy content, and combustion temperature.

A strong positive correlation was observed between CO and CH_4 concentrations in the flue gas (Spearman's $\rho = 0.93$). On average, 0.10 ± 0.04 mol of CH_4 were detected per mol of CO. When expressed as emission factors, this equates to 0.058 ± 0.022 kg of CH_4 per kg of CO corresponding to an approximate CO to CH_4 mass ratio of 17:1. However, the relationship between CO and CH_4 concentrations was not linear but followed a power-law function. Specifically, CH_4 increased with CO in a nonlinear, accelerating manner: a 1% increase in CO concentration was associated with a 1.65% increase in CH_4 concentration over the range of values observed (Figure 5).

4 | Discussion

Pyrolysis technologies play a crucial role in PyCCS, as they transform biomass carbon into stable biochar, thus enabling long-term carbon dioxide removal (given that rapid oxidation of biochar is prevented). Today, a wide array of pyrolysis technologies exists, ranging from traditional charcoal-making to modern industrial plants and artisan kilns developed exclusively for biochar production. The suitability and effectiveness of these pyrolysis technologies to deliver carbon dioxide removal depend on several factors, not least the emissions associated with biochar production.

In our study, mean CO and CH_4 emission factors ranged from 34 to 437 g kg^{-1} biochar and 1.4 to 38.8 g kg^{-1} biochar, respectively. All feedstocks with moisture contents < 25% showed low methane emissions, with all values being < 5 g CH_4 kg^{-1} biochar, except semi-moist wheat straw. In contrast, moist feedstocks (moisture ≥ 25%), particularly giant reed, coffee wood, and guadua bamboo exceeded 30 g CH_4 kg^{-1} biochar. Recent work from other authors (Cornelissen et al. 2023, 2024) reported similar results (< 5.5 g CH_4 kg^{-1} biochar) for most feedstocks with < 15% moisture (except for dense, finely grained feedstocks). However, Cornelissen et al. (2023) also reported extremely high emissions of up to 605 g kg^{-1} for moist feedstocks, which is more than one order of magnitude higher than those of the wettest feedstock still possible to pyrolyze in the present study (47 g CH_4 kg^{-1} biochar). Based on the present study, we suppose that the extremely high CH_4 emissions reported from one experiment without replication may have been an artifact.

Depending on the pyrolysis technology, emission factors vary widely. For industrial pyrolysis, emission factors of below 10 g CO and 1 g CH_4 per kg biochar have been reported (Flatabø et al. 2023; Sørmo et al. 2020; Cornelissen et al. 2024). In comparison, mean emissions of traditional charcoal making (i.e., earth mound kilns and others), where found to be 223 g CO kg^{-1} (Pennise et al. 2001) and 32 CH_4 kg^{-1} (Chidumayo and

Gumbo 2013). Compared to traditional charcoal making, mean methane emissions in flame curtain pyrolysis can be roughly an order of magnitude lower for dry feedstocks (2.9 g CH_4 kg^{-1} biochar), supporting lower-emission decentralized biochar production.

Building on these advantages, among others, Kon-Tiki biochar production has been recognized as an artisan biochar production technology under the Global Artisan C-Sink Standard, a framework that enables certification of carbon dioxide removal via small-scale, decentralized biochar production in low income to higher middle income countries (CSI 2024). Within this standard, a default methane emission factor (i.e., 30 g CH_4 kg^{-1} biochar) was applied for Kon-Tiki pyrolysis of any feedstock with a maximum permitted moisture content of 25% (CSI 2024). This default emission factor is derived from the first study on the topic by Cornelissen et al. (2016), who measured CH_4 emissions across multiple feedstocks with 15% to 25% moisture content.

Our results reveal a clear trend of decreasing methane emissions with lower feedstock moisture. Combined with other recent studies (Cornelissen et al. 2023, 2024), these results show that a general methane emission factor as the 30 g CH_4 kg^{-1} biochar currently applied in the Global Artisan C-Sink standard (CSI 2024), does not reflect the high potential to reduce CH_4 emissions through reducing feedstock moisture. Across all dry and most semi-moist feedstocks, the methane emission factors were 1/3 to 20 times below the current default value of the Global Artisan C-Sink Standard, regardless of the feedstock type (i.e., woody branches, straw, corn cobs, or bamboo). This pattern is confirmed across studies (Cornelissen et al. 2023, 2024). In contrast, moist feedstocks with a water content > 25% cause methane emissions to increase sharply, and in some cases exceed 30 g kg^{-1} biochar. Therefore, feedstocks with > 25% moisture content should not be used for flame curtain pyrolysis. Ideally, feedstock moisture should be < 15% where the methane emission factor is consistently below 5 g kg^{-1} biochar. For moisture contents between 15% and 25%, the current default emission factor of 30 g CH_4 kg^{-1} biochar seems appropriate.

For open burning, CH_4 emissions ranged from 0.2 to 10.4 g kg^{-1} feedstock, consistent with reported values (0.7–10 g kg^{-1}; Sahai et al. 2007; Christian et al. 2003; Hayashi et al. 2014). In our experiments, the biomass was deliberately piled before burning, whereas in field situations, feedstock may be piled and burnt or burnt as it is in situ. The latter may cause varying combustion dynamics and emission factors. Nevertheless, CH_4 emission data from whole-field wheat straw burns (3.4–9.6 g CH_4 kg^{-1} feedstock; Sahai et al. 2007; Kudo et al. 2014; Li et al. 2007) align well with our results, indicating that our piled burns are representative of typical field emissions.

Similar to the results for the Kon-Tiki, we found elevated CH_4 emissions for open burning of moist wheat straw. Field studies report moisture contents > 20% for straw at the time of burning (Oanh et al. 2011). At these levels, we found CH_4 emissions of 6.7–10.4 g kg^{-1} for wheat straw, compared to significantly lower emission factors for dry wheat straw (3 g kg^{-1}, at 10% moisture). Hayashi et al. (2014) similarly reported a threefold CH_4 increase in barley and rice straw burning when moisture rose from 12% to 20%. These results show that moisture content impacts methane emission in both open burning and flame curtain pyrolysis.

Comparing emission factors for CO_2, CO, CH_4 and C_3H_8 for the same moisture category, emissions were lower for flame curtain pyrolysis. The Kon-Tiki significantly reduced methane emissions for wheat straw when compared to open burning emissions. As straws are a crop residue of global importance, with 35 Tg wheat straw being openly burnt annually in India alone (Sahu et al. 2021) and 120 Tg of different straws being burnt in China annually (Hong et al. 2023), in-field straw pyrolysis with Kon-Tiki kilns holds the promise of significant GHG-emission reductions.

The climate balance between open burning and flame-curtain (Kon-Tiki) pyrolysis of crop residues reveals clear differences. Compared to open burning, pyrolyzing one ton of straw in the Kon-Tiki avoided CO and CH_4 emissions of 36 kg and 3.6 kg on average, respectively. These values should be regarded as conservative because we could not completely assess the smoldering phase during open burning events due to lack of gas flow and dilution with ambient air. Completion of the smoldering phase until self-extinction would have led to higher carbon losses and comparatively higher amounts of CO and CH_4.

Beyond emission avoidance, Kon-Tiki pyrolysis produced ~200 kg of biochar with a carbon content of 72%, corresponding to a carbon sink of > 500 kg CO_2e (75% of which can be considered persistent, CSI 2024), generating a substantial negative emissions, when biochar is applied to the soil. Therefore, pyrolysis is a suitable approach to effectively reduce greenhouse gas emissions from open burning of crop residues, as suggested by Khalid et al. (2022).

In the Kon-Tiki, higher fuel moisture content increases the energy demand for drying, as a substantial fraction of the heat released by combustion is consumed by water evaporation (latent heat), thereby reducing combustion zone and flue gas temperatures. This effect is commonly referred to as evaporative cooling. In addition, the resulting steam effectively dilutes the concentration of combustible gases, reduces energy density, and, therefore cools the combustion zone. Consequently, higher water contents promote longer residence times of the feedstock under low temperature smoldering conditions, which favors incomplete oxidation of the resulting gases and elevated CH_4 release by delaying (or disrupting) sustained flaming combustion (Vakkilainen 2017).

In this study, the feedstock type also played an important role, indicating that moisture alone does not fully explain methane emission variability. Using the lower heating value on a wet basis (LHV_{wb}) as an explanatory variable (instead of the feedstock moisture content) improved the model's explanatory power (by 0.11, $R^2 = 0.54$ to 0.65). While other authors have noted that LHVs vary little among potential flame curtain pyrolysis feedstocks and that the effect of the LHV on emission factors may thus be limited (Cornelissen et al. 2024), it is important to emphasize that the wet-basis LHV remains a valuable metric, because it combines the influence of the moisture content and the intrinsic calorific value of a feedstock. Thus, the wet-basis LHV was found to be a powerful metric that may, to some extent, substitute for feedstock type and water content in explaining methane emissions. Future research should test a broader range of feedstocks and moisture conditions to evaluate whether wet-basis LHV can serve as a generalizable parameter for predicting CH_4 formation in flame curtain pyrolysis systems. If confirmed, wet-basis LHV could support operational guidance and monitoring for flame curtain pyrolysis.

In our study, CO and CH_4 showed a strong relationship, aligning with similar findings from earlier works (Sahai et al. 2007; Andreae 2019; Li et al. 2007; Hayashi et al. 2014). An analysis of the data included in Andreae (2019) showed that similar ratios between CO and CH_4 (13 g CO per g CH_4) were found for open burning of agricultural residues. These values are representative of the values we found for open burning of wheat straw and similar to values for moist feedstocks in flame curtain pyrolysis (Table S1), confirming the validity of our findings.

Flue gas temperatures can be used to gain insights into pyrolysis performance. Here, we found substantially reduced emissions at higher temperatures. This finding is consistent with improved combustion efficiency at elevated temperatures (Zhang et al. 2013), which enhances methane oxidation (Burgoyne and Hirsch 1954; Dryer and Glassman 1973). The observed temperatures are in turn a product of oxidation, influenced by the moisture content and the calorific value (LHV) of the feedstock. They can be monitored in real-time during pyrolysis process. Measuring gas temperature could thus serve as a proxy to effectively control methane emission factors. Based on our data, three classes could be proposed: (I) temperature > 190°C, emission factors < 5 g CH_4 kg^{-1} biochar, (II) temperature range from 131°C to 190°C, emission factor < 15 g CH_4 kg^{-1} biochar, and (III) temperature range from 95°C to 130°C, emission factor < 30 g CH_4 kg^{-1} biochar. If flue gas temperatures are used for monitoring, Kon-Tiki kilns would need to be fitted with a flue stack to enable continuous temperature measurement at a defined position above the flame curtain. However, temperature thresholds would need to be calibrated for each flame curtain pyrolysis device and chimney type.

In addition to the parameters investigated in this study (feedstock moisture content, feedstock LHV_{wb}, and gas temperature), the timing of feedstock addition represents an important operational factor and a potential source of variability. If feedstock is added too rapidly, the flame curtain can be disrupted, leading to smothering of the flames, incomplete combustion of pyrolysis gases, and potentially incomplete pyrolysis of lower feedstock layers. Conversely, excessively slow feedstock addition may allow previously pyrolyzed material to oxidize, increasing ash formation. Both could be monitored with continuous flue gas measurements. In the present study, pyrolysis was conducted in accordance with established operational guidelines, and adequate training of artisan biochar producers is crucial to ensure good performance of flame curtain pyrolysis. Despite the inherent sensitivity of flame curtain pyrolysis to operator practice, relatively low emissions have been reported for dry feedstocks throughout studies (Cornelissen et al. 2023, 2024), showing that the risk of higher emissions is reduced the dryer the feedstock. Due to the wide range of feedstocks and moisture contents tested, we consider the emission factors described here robust and recommend to prioritize feedstock drying (to moisture contents < 15%) in any operation using Kon-Tikis for biochar production to minimize methane emissions.

Author Contributions

Simon Lotz: conceptualization, investigation, writing – original draft. **Nikolas Hagemann:** writing – review and editing. **Dirk Hölscher:** supervision, writing – review and editing. **Hans-Peter Schmidt:** funding acquisition, conceptualization, writing – review and editing.

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Conflicts of Interest

The authors declare that partial funding for this study was provided by Sting—Stockholm Innovation & Growth AB (Stockholm, Sweden) who had no role in the study design, data collection, data analysis or interpretation of results. H.-P.S. reports a relationship with Carbon Standards AG that includes: board membership. H.-P.S. and N.H. are co-authors of several Carbon Standards AG guidelines for the certification of biochar (EBC) and biochar-based carbon sinks (EBC C-Sink/Global Biochar C-Sink, Global Artisan C-Sink). The other authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.18171095.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.