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Methane Emissions from Artisanal Biochar Production
A White Paper

by Simon Lotz[1] & Hans-Peter Schmidt[1*]

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[1] Ithaka Institute for Carbon Strategies, Ancienne Eglise 9, CH-1974 Arbaz, Switzerland

* Corresponding Author: schmidt@ithaka-institut.org

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Executive Summary
Methane (CH_4) is a potent greenhouse gas that causes a direct radiative forcing effect. With a mean residence time of 12 years in the atmosphere, the global warming potential of methane is at least 80 times higher than CO_2 over 20 years and 27 times higher over 100 years. Despite its short residence time, anthropogenic methane emissions contribute to around 25% of global warming. Overall, more than half of global methane emissions stem from anthropogenic sources, namely agriculture (40%), fossil fuel processing (35%), waste management (20%), and biomass combustion (5%). The present white paper investigates methane emissions from flame curtain pyrolysis (i.e., artisan biochar production) and open biomass burning, aiming to quantify emission factors and provide recommendations to reduce these crucial emissions.
In general, methane can be produced through both biological and thermochemical processes. While biological methane production is typically associated with anaerobic decomposition, thermochemical methane formation occurs during combustion and pyrolysis. This study focuses on the latter, where methane is a product of incomplete combustion of biomass. When biomass is heated to elevated temperatures (> 200 °C), it releases flammable volatiles such as carbon monoxide (CO), hydrogen (H_2), and light hydrocarbons (CxHy) like CH_4. When these volatiles compounds are oxidized (e.g., by passing through a fire zone), the resulting products are CO_2 and H_2O. However, if the combustion of the released volatiles is incomplete, molecules like CH_4 and CO are emitted into the atmosphere. During flame curtain pyrolysis or an open biomass burning event, factors such as low gas temperatures and limited oxygen supply may prevent the full combustion of volatiles (and thus the oxidation of these gases to CO_2) and cause significant methane emissions. Higher feedstock moisture further prolongs drying and devolatilization, lowers burning temperatures, and may hinder combustion, potentially enhancing smoldering and increasing CO and CH_4 emissions.
In pyrolysis biomass is heated under the near absence of oxygen to temperatures above 350 °C. It is applied to traditional and modern charcoal and biochar making. A special pyrolysis technique used in artisan biochar making is the flame-curtain pyrolysis. In this typical artisan biochar production, feedstock is added and pyrolyzed layer by layer in an open kiln (i.e., the Kon-Tiki) heated by a covering flame curtain. The flame curtain above the pyrolyzing feedstock consumes the oxygen from the air, creating oxygen-starved pyrolysis conditions below the flame curtain. Volatiles (i.e., the pyrolysis gas) emitted during the outgassing of the biomass-feedstock in the kiln are mostly burnt (to CO_2 and H_2O) when passing the fire carpet above the feedstock layers. However, not all volatiles are captured by the flame curtain. Some molecules, such as CH_4 and CO, pass the flame zone unoxidized and are emitted to the atmosphere.

In the present white paper, we assessed the CH_4, CO and CO_2 emissions from Kon-Tiki pyrolysis for various feedstocks and moisture contents. The Kon-Tiki emissions were then compared with emissions that occurred when the same biomass feedstock was burned in an open setup to simulate open burning of crop residues.

When using the same feedstock, methane emissions of the Kon-Tiki were on average 36% lower than those from simulated open burning. Similarly, CO emissions decreased by 35% on average.

In general, methane emissions increased with increasing feedstock moisture content. Here we grouped feedstocks in three moisture content categories dry (≤ 15%), semi-moist (16-24%) and moist (≥25%). For dry and semi-moist feedstocks (moisture content < 25%), emission factors were significantly lower than the methane emission factor of 30 kg CH_4 per ton of biochar, considered in the Global Artisan C-Sink Standard (CSI, 2024). For woody biomass with a moisture content below 25%, average emission factors were around 5 kg CH_4 per ton of biochar. However, semi-moist wheat straw exhibited higher emissions, reaching up to 20 kg CH_4 per ton of biochar. According to the extensive dataset collected for this study, only feedstocks with elevated moisture contents (> 25%) produced higher methane emissions, ranging from 30 to 40 kg CH_4 per ton of biochar.

The presented data confirm the low Kon-Tiki emission factors described by Cornelissen et al. (2023) for dry feedstocks. However, the extremely high methane emission factor that Cornelissen et al. (2023) found for wet feedstock (twigs and leaves) could not be confirmed; they were an order of magnitude higher than the highest emissions measured from the wettest feedstock (giant reed).

The moisture content of the feedstock emerged as the most critical factor influencing methane emissions during the Kon-Tiki process. The kiln's flue gas temperature also offers valuable process insights. Continuous flue gas temperature monitoring can be used for methane emission factor monitoring, The moisture content of the feedstock is particularly crucial because it directly affects the combustion process and, thus, the temperature profile.

Biomass with low moisture content allows for a more complete combustion, whereas higher moisture levels prevent the full combustion of volatile compounds. The feedstock moisture must first evaporate before the main pyrolysis reactions can set in. Water evaporation consumes heat and lowers temperatures through evaporative cooling. Additionally, the formation of steam obstructs the efficient mixing of combustion air (i.e., oxygen) with the rising pyrolysis gas. As a result, a portion of the released methane is emitted without being oxidized to CO_2.

To ensure low methane emissions, the feedstock must be thoroughly dried. The feedstock moisture content should either be monitored directly using biomass moisture analysis or indirectly via continuous flue gas temperature monitoring. This approach will optimize flame curtain pyrolysis and minimize methane emissions. With very dry feedstock (< 15% moisture content), CH_4 emissions were always below 5 kg CH_4 per ton of biochar, significantly lower than the default value of the Global Artisan C-Sink Standard.

5 kg CH_4 per ton of biochar, representing the global warming potential of 400 kg CO_2e over 20 years (versus a carbon sink of circa 2000 kg CO_2e) can be compensated by the semi-persistent carbon (SPC) fraction of a Kon-Tiki biochar or by planting trees and maintaining their growth for at least 20 years.

The present White Paper is based on *Methane Emissions From Flame Curtain Pyrolysis (Kon-Tiki)* published 2026 in the Journal Global Change Biology and Bioenergy by Lotz et al. (https://onlinelibrary.wiley.com/doi/10.1111/gcbb.70108).

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1 The effect and fate of methane in the atmosphere

Methane (CH_4) is a potent greenhouse gas because it has a direct radiative forcing. This means the molecule, as a greenhouse gas, traps heat in the atmosphere. It does this primarily by absorbing thermal energy (longwave radiation) emitted from the Earth's surface, preventing its dissipation into space. It does so more efficiently than CO_2 (Collins et al. 2018) and has, therefore, an 80 to 86 times higher global warming potential during the first 20 years after the emission (Myhre et al. 2013, Foster et al. 2021).

Methane is emitted through natural and anthropogenic sources. Anthropogenic sources contributing to increasing atmospheric methane concentrations include fossil fuel extraction, agriculture, waste management (especially landfills), and the combustion of fossil fuel and biomass, which altogether account for 60% of global methane emissions (UNEP 2021).

The global mean CH_4 gas concentration in the atmosphere has risen to around 2 ppm, which is estimated to be more than 150% higher than in preindustrial times (Myhre et al. 2013). Compared to the current global mean CO_2 concentration (420 ppm), the atmospheric CH_4 concentration is 200 times lower. Yet, due to methane's much stronger warming effect, the impact on global warming is significant. The lifespan of methane is comparatively short compared to other GHGs. The average persistence of methane in the atmosphere is 12 years (Myhre et al. 2013), where it decays through oxidation with atmospheric hydroxyl radicals (HO•), ultimately forming water vapor and CO_2.

To compare the relative climate impact of greenhouse gases between each other, the effects of emissions are expressed as the global warming potential (GWP) over a defined period in CO_2 equivalent (CO_2e). This metric is the average radiative forcing of an emission of a specific greenhouse gas over a defined time compared to the effect of CO_2 during the same time (Balcombe et al. 2018). The global warming potential (GWP) of methane is 80 to 86 times higher than CO_2 in reference to a 20-year time frame (GWP20) and 25 to 30 times higher (27 for non-fossil CH_4 according to IPCC AR6) in reference to a 100-year time frame (Myhre et al. 2013; Forster et al. 2021). After 20 years, almost all emitted CH_4 has been broken down through atmospheric processes, and its direct radiative forcing ceases, with only its decay products, CO_2 and H_2O, continuing to contribute to global warming.

Methane emissions have contributed around 25% to global warming since the pre-industrial era, making it the second largest contributor to climate change after CO_2 (Etminan et al. 2016; Myhre et al. 2013). Weighted by the GWP100, methane contributes around 18% to global warming annually. However, considering that more than 99% of its climate forcing occurs in the first 20 years, the GWP20 must be applied when measuring the accumulated global warming effect. Minimizing methane emissions and rapidly offsetting the remaining share within a timeframe comparable to methane's strongest climate impact (the first 12 years after emission) is therefore crucial for climate change mitigation in the next decade.

The largest shares of methane emissions are attributed to agriculture (mostly due to ruminant livestock and rice cultivation, 40%), fossil fuel extraction, transport, and refining processes (35%), and landfill and waste management (20%). Here, we want to focus on methane emissions from artisanal pyrolysis processes and from in-field crop waste burning, the latter contributing to around 5% of the overall annual anthropogenic CH_4 emissions of around 364 Mt per year (UNEP 2021; Jackson et al. 2020; Saunois et al. 2020).

2 The mechanisms of methane production in open fires and Kon-Tiki pyrolysis

2.1 Open fires

The open burning of biomass typically occurs in four partly overlapping phases:

1. Drying and Heating: The biomass heats up and dries.
2. Devolatilization and Ignition: As the biomass reaches higher temperatures (200-300 °C), it begins to break down (thermal decomposition), releasing a mixture of flammable volatile gases, including methane (CH_4), carbon monoxide (CO), and various hydrocarbons.
3. Flaming Combustion: Given that sufficient oxygen and an ignition source are present, these volatiles can ignite and burn vigorously with visible flames. This phase is characterized by high temperatures and relatively efficient oxidation, ideally converting the carbonaceous gases into CO_2. Concurrently, a part of the biomass is transformed into char.
4. Char Oxidation (Smoldering Combustion): After the majority of volatile gases have been consumed or released, the remaining solid carbonaceous material (char) undergoes flameless, glowing combustion. This process occurs directly on the char surface and is typically characterized by lower temperatures due to stronger oxygen limitations compared to flaming combustion.

While these distinct processes are well-defined in theory, they often overlap in time and space during real-world biomass burning (Koppmann et al. 2005; Nussbaumer 2003; Price-Allison et al. 2019). The total amount of methane (CH_4) emitted from an open fire is directly and significantly impacted by the interplay of these processes. During devolatilization, methane is released as a volatile gas; if the gases are not subsequently ignited into a flame, they will be emitted and contribute to global methane emissions. During flaming combustion, ideal conditions may lead to a rather complete oxidation of all flammable gases, forming CO_2 and H_2O. However, as the degree to which this complete combustion occurs depends on factors such as oxygen availability and flame temperatures, significant amounts of CH_4 may still escape unburnt. During smoldering, oxidation is inherently less efficient due to oxygen limitations and lower temperatures, leading to a higher proportion of incomplete combustion products, including CH_4, CO, NMVOCs (non-methane volatile organic compounds), and PM (particulate matter).

Acknowledging that these processes all occur in parallel during open burning of biomass, the balance between flaming and flameless (i.e., devolatilization and smoldering) processes is primarily governed by feedstock characteristics, weather conditions and fire conditions. Although, open biomass burning has been widely identified as a source of CH_4 emissions of global importance large uncertainty remains regarding the magnitude of the emissions per ton of biomass (i.e., the emission factors). Reported emission factors range from 1 to 20 kg CH_4 per ton of biomass (Koppmann et al. 2005). Crop residue burning, along with man-made wildfires, is the primary source of anthropogenic fire emissions. Studies on crop residue burning emissions have been carried out under field and lab conditions for various feedstocks and are summarized in Table 1.

Table 1: Literature review of emission factors for open field burning in comparison to our data. Emission factors refer to feedstock (FS) dry weight (dw) in kilogram per metric ton.

Feedstock	Moisture	Emission factors in kg t^{-1} feedstock (dw)			Reference
	%	CO_2 kg t^{-1} FS (dw)	CO kg t^{-1} FS (dw)	CH_4 kg t^{-1} FS (dw)	
Wheat straw	14	1787	28	3.6	Sahai et al. (2007)
Wheat straw	12	526	42	2.01	Hayashi et al. (2014)
Wheat straw	20	952	77	3.62	Hayashi et al. (2014)
Wheat straw	10	1470	60	3.4	Li et al. (2007)
Wheat straw	***14***	***1184***	***52***	***3.2***	***Mean literature***
Wheat straw	10	1447	50	3.0	this study
Wheat straw	18	1394	85	6.7	this study
Wheat straw	26	1342	115	10.4	this study
Wheat straw	***18***	***1394***	***83***	***6.7***	***Mean this study***
Rice straw	10.6	1111	44	2.1	Miura and Kanno (1997)
Rice straw	14	711	70	4.1	Miura and Kanno (1997)
Rice straw	11	803	27	0.7	Hayashi et al. (2014)
Rice straw	20	946	59	2.47	Hayashi et al. (2014)
Rice straw	26	1147	97		Oanh et al. (2011)
Rice straw	*25.5*	1216	180	9.59	Christian et al. (2003)
Rice straw		1460	34.7	1.2	Gadde et al. (2009)
Rice straw		1394	87.1	3.6	McMeeking et al. (2009)
Rice straw	***18***	***1099***	***75***	***3.4***	***Mean literature***
Barley straw	11	983	47	1.47	Hayashi et al. (2014)
Barley straw	20	1068	93	4.55	Hayashi et al. (2014)
Maize stover	9	1350	53	4.4	Li et al. (2007)
Crop residues		1515	92	2.7	Andreae and Merlet (2001)
Crop residues		1664	85.6	5.01	Akagi et al. (2011)
Crop residues		1430	76	5.7	Andreae (2019)
Crop residues		1664	85.56	5.17	Yokelson et al. (2011)
Crop residues		***1568***	***85***	***4.6***	***Mean literature***
Orchard pruning	10	1350	13.3	0.2	this study
Orchard pruning	20	1399	19.8	0.5	this study
Orchard pruning	25	1430	23.0	0.9	this study
Reed	39	1420	79.5	6.5	this study
Pruning/Reed	***24***	***1400***	***34***	***2.0***	***Mean this study***

Tropical forest		1580	104	6.8	Andeae and Merlet (2001)
Tropical forest		1620	104	6.5	Andreae (2019)
Conifer wood	17	1708	66.3	5	Springsteen et al. (2015)
Conifer wood (smoldering)	17	1511	157.6	13.5	Springsteen et al. (2015)
Douglas fir	wet	1689	82	5.7	Aurell et al. (2017)
Douglas fir	dry	1785	29	1.1	Aurell et al. (2017)

From the literature data we can summarize that higher moisture content of the feedstock:

- Results in lower burning temperature (through evaporative cooling),
- Extends the drying and devolatilization phase,
- Inhibits the ignition of flames.

As smoldering may take place already at lower temperatures, higher CO and CH_4 emissions are caused (Vakkilainen 2017). During smoldering with no or incomplete flame cover, heavy smoke production may occur. Limited oxygen supply may further prolong the smoldering phase by inhibiting flame ignition (Price-Allison et al. 2023).

The importance of feedstock moisture content on gas emission factors of combustion processes in general and open crop burning in specific was also shown in various studies (Hayashi et al. 2014; Price-Allison et al. 2023; Miura and Kanno 1997).

Hayashi et al. (2014) found higher CH_4 emissions for wet straws (rice, barley, and wheat), with a threefold increase of CH_4 emissions for barley and rice when the moisture content increased from 12% to 20% (Table 1). In Thailand the average moisture content of rice straw was roughly 26% (Oanh et al. 2011). While the moisture content of straw that is openly burned on the field can vary highly, moisture contents above 20% are frequent (Oanh et al. 2011).

Arai et al. (2015) showed that for the burning of rice straw, methane emissions are largely connected to the moisture, but also to pile size (kg per pile), with larger piles prone to emitting higher emissions. This was also confirmed by Oanh et al. (2011) for particulate matter (PM) emissions. They report, on average, three times higher PM emission factors for piled biomass compared to the burning of standing biomass (stubble).

From the available literature we can summarize, that in principle dry biomass, good aeration (oxygen supply), and sufficient calorific value (energy content of the feedstock) lead to longer fire durations and a greater share of flaming combustion, resulting in lower methane emissions. In contrast, high moisture contents in the biomass, poor aeration, and low calorific value result in smoldering domination of the burning event resulting in higher methane emissions. However, regarding the direct comparison of emission factors between open burning and flame curtain pyrolysis, knowledge gaps remain.

2.2 Flame curtain pyrolysis

Biochar is created through pyrolysis, which is the thermochemical decomposition of biomass under oxygen-poor conditions. Pyrolysis differs from open burning, where biomass combusts freely with ample oxygen and is turned mostly into ash and gaseous combustion products.

During flame curtain pyrolysis (i.e., in a Kon-Tiki), pyrolysis conditions are created in an open metal kiln or soil pit. Feedstock is added and pyrolyzed layer by layer, maintaining flames on top of the uppermost layer. Hence, combustion air (i.e., oxygen) is consumed by these flames and does not penetrate the pyrolyzing feedstock layers, preventing further oxidation of the char. Pyrolysis gases emitted during the devolatilization phase of the biomass are forced through the flame curtain and are mostly burnt to CO_2 and H_2O (Cornelissen et al. 2016; Schmidt and Taylor 2014).

To successfully perform flame curtain pyrolysis, the timing of adding new feedstock layers is

crucial. If feedstock is added too quickly, the flame curtain will be interrupted, and smoldering will occur for a certain time, resulting in the emission of unburnt pyrolysis gas (including CH_4). In contrast, if biomass layers are added too slowly, the pyrolyzed feedstock may oxidize, resulting in the formation of ash. At the end of the process, when no more feedstock is added, further oxidation of the char has to be prevented by quenching or air-tight sealing of the char.

In comparison to common open burning of crop residues, flame curtain pyrolysis favors devolatilization and volatile combustion while it avoids or reduces char combustion.

In this context, a continuous flame curtain is of utmost importance, because many organic and inorganic compounds are released from the biomass including CO, C_xH_y, tar, unburnt carbon, H_2, NH_3, a large variety of volatile organic compounds (VOCs; Wang et al. 2014). These compounds are combusted to products of complete combustion (mainly CO_2, H_2O, NO_x) when passing the flame curtain. However, a variety of factors interact and determine how complete pyrolysis gases are combusted. Literature presents methane emission factors of traditional charcoal and biochar making with a wide range of values. Andreae and Merlet (2001) present an overall mean of 10.7 kg CH_4 per ton feedstock (dry weight), representing approximately 40 kg CH_4 per ton of charcoal/biochar.

Emissions from charcoal production can be significantly reduced and productivity increased by utilizing improved kilns compared to traditional earth mound kilns (Tazebew et al. 2024). Methane emissions from traditional charcoal production from woody biomass (*Eucalyptus camaldulensis*, 15% moisture content) were assessed to be around 52 kg t^{-1} charcoal (i.e., 12.3 kg t^{-1} feedstock, dry weight) and kiln improvement reduced the CH_4 emissions to 28 kg t^{-1} charcoal (9.4 kg t^{-1} feedstock, dry weight) in Ethiopia (Tazebew et al. 2024). Similar results were found by Pennise et al. (2001) and Sparrevik et al. (2015). Non-retort kilns showed average methane emission factors of 54 kg t^{-1} charcoal, whereas 24 kg t^{-1} charcoal was reported for retort kilns (Sparrevik et al. 2015). Similar or stronger reductions of emission factors were also found for carbon monoxide emissions (Sparrevik et al. 2015; Tazebew et al. 2024).

Cornelissen et al. (2016) demonstrated that similar emission factors were achieved with low-investment Kon-Tiki kilns based on the principle of flame curtain pyrolysis, aimed at high-quality biochar production. They report mean emission factors for CO and CH_4, of 54 and 30 kg t^{-1} biochar, respectively. However, a large variability of emission factors indicated that feedstock characteristics and know-how (regarding kiln operation) play a crucial role for emission factors.

The pivotal role of feedstock drying and the utilization of dry feedstock for Kon-Tiki kiln operation was highlighted by Cornelissen et al. (2023; 2024). They report low CH_4 emission factors of < 5.5 kg t^{-1} biochar for dry feedstock (< 15%), but extremely high emission factors of 605 kg t^{-1} biochar for wet feedstock (> 40%).

What is true for combustion in general, also plays an important role in Kon-Tiki pyrolysis; combustion efficiency largely depends on the feedstock's moisture content, calorific value, and bulk density. These factors have to be considered by the Artisan when producing Kon-Tiki biochar.

2.3 Influence of the feedstock moisture content

Higher temperatures and a continuous flame curtain can be achieved by utilizing dry feedstock.

Biomass with a low moisture content facilitates complete combustion of the gases emitted, while higher feedstock moisture content hampers the complete combustion of volatiles, such as methane in various forms. The following reasons apply:

(1) Most of the water needs to be evaporated before the volatiles can be combusted.
(2) Water evaporation consumes large amounts of heat (energy),
(3) lowers the (combustion or pyrolysis) temperatures (Nussbaumer 2003; Koppmann et al. 2005), and
(4) increases the steam formation, impairing adequate mixing with air.
(5) It also fosters overlaps between volatile combustion and char combustion as residual moisture remains partly in the feedstock,

impeding devolatilization in some parts of the kiln while in other parts char combustion is occurring already (Price-Allison et al. 2023).

Consequently, a high moisture content extends the initial heating period before the release of pyrolysis gases. During the drying and devolatilization period, large amounts of volatile organic compounds (like methane) are emitted (Koppmann et al. 2005), but not combusted as the flame curtain may not have been established yet. Once the feedstock is dried, the gas flaming phase may start, given that there is finally enough heat for a continuous gas release from the feedstock (Koppmann et al. 2005).

In consequence, dry feedstock, temperatures above 300 °C, flame contact, and sufficient oxygen availability are expected to result in lower CH_4 emissions while promoting the formation of complete combustion products (CO_2, H_2O). However, in such an open process, where gas flow cannot be fully controlled (Chouchene et al. 2010; Koppmann et al. 2005), some residual volatiles will still be emitted without complete combustion. The magnitude of these processes and the resulting emission factors were assessed during an extensive measurement campaign, which is presented in the following chapters.

3. Global Artisan C-Sink Guidelines

The Kon-Tiki was introduced as an affordable bridge technology for smallholder, small-scale biochar production. It can be used for a wide variety of feedstock types and enables high-quality biochar production (Cornelissen et al. 2016; CSI 2024). Biochar production and application by smallholders in tropical low and lower middle-income countries can be a key tool to increase crop yields while transforming crop residues into a stable carbon pool via pyrolysis (Schmidt et al. 2021; Melo et al. 2022; Ye et al. 2020). By promoting biochar production from agricultural residues, the widely common open field burning of crop residues can be replaced, and thus several negative effects of the practice, such as high GHG emissions and air pollution, can be avoided (Estrellan and Iino 2010; Gadde et al. 2009; Akagi et al. 2011; Christian et al. 2003; Hayashi et al. 2014; Li et al. 2007; Stockwell et al. 2014).

Kon-Tiki biochar can be certified under the "Global Artisan C-Sink: Guidelines for Carbon Sink Certification for artisan biochar production" (CSI 2024). The resulting climate service (a C-Sink credit) can be sold on the international voluntary market and generate additional income for farmers, creating economic incentives for the carbon sink economy. The Global Artisan C-Sink requires: "Stringent monitoring, reporting, and verification (MRV) […] to create trustworthy carbon sinks on smallholder farms, but also on larger estates, within farmers cooperatives, on public land, and in biomass processing industries. The C-sinks and the emissions caused by establishing the C-sinks must be transparently accounted for, controlled, and inscribed in the Global C-Sink Registry" (CSI 2024).

The Global Artisan C-Sink guidelines define in detail, how Kon-Tiki biochar production must be monitored, verified, and certified.

> The overall principles for successful certification include:
>
> "1. The biomass was procured sustainably, e.g., farm residues, derived from biomass processing waste streams, or disaster debris but no forest wood […].
> 2. It was dried and/or aerated to avoid decomposition during storage and subsequent greenhouse gas emissions during pyrolysis […].
> 3. The pyrolysis was done with care by trained artisans to reduce the formation of non-CO_2-greenhouse gas emissions during pyrolysis to a minimum […].
> 4. The methane emissions caused during production are offset through equivalent emission avoidance, certified tree plantations, or other certified temporary carbon sinks […].
> 5. The biochar was applied to the soil or C-sink eligible materials and not burnt or sold for burning […].
> 6. The carbon sink was registered in the Global C-Sink Registry […].
> 7. The artisan members of a C-Sink Network or Carbon Village are paid directly for the climate service, and the amount the artisans and cooks receive is transparently communicated.
> 8. The country where the biochar was produced counts among the Low-Income, Lower Middle Income, and Higher Middle-Income countries as defined by the World Bank classification of countries" (CSI 2024).

Regarding the fourth point above, the Global Artisan C-Sink assumes a generic methane emission factor of 30 kg CH_4 t^{-1} biochar for Kon-Tiki biochar production, which is based on the first study on the topic by Cornelissen et al. (2016).

In the following, we refer to the Global Artisan C-Sink Standard (CSI 2024) Version 2.1A released on June 15, 2024 as Global Artisan C-Sink Guidelines.

4. Results of new systematic emission testing

4.1 Methane emissions of Kon-Tiki pyrolysis

In total, 36 Kon-Tiki runs were performed, covering five feedstocks and a wide range of moisture contents from 10% to 39%. The feedstock dry weight was kept constant for varying moisture contents of the same feedstock used in the "Kon-Tiki" or for "Open field burning" to facilitate comparability.

The runs with high moisture contents were performed to address potential worst-case scenarios. It needs to be underlined here that for runs with feedstock moisture contents above 25% a continuous flame cap could not be maintained. Outgassing and pyrolysis occurred largely under smoldering combustion conditions without the presence of flames and thus mostly without oxidizing the pyrolysis gases. Under the Global Artisan C-Sink Standard, such sub-optimal practices would be excluded.

A strong relationship between feedstock moisture content and the methane emission factor was found. The lowest methane emission factors were detected for coffee stem wood, orchard pruning, and giant reed (*Arundo donax*), presenting less than 16% moisture content (1.4 to 1.7 kg CH_4 t^{-1} biochar, Figure 1, Table 2). The highest mean CH_4 emissions were found for Guadua (the Colombian timber bamboo, *Guadua angustifolia*) with 27% moisture content (Table 2, 38 kg CH_4 t^{-1} biochar).

Woody biomass with a moisture content below 25% showed methane emissions factors below 5 kg CH_4 t^{-1} biochar. Dry wheat straw (10% moisture content) had similar emission factors (Figure 1, Table 2). However, semi-dry straw (18% moisture content), showed higher CH_4 emission factors of 20 kg CH_4 t^{-1} biochar, compared to woody biomass with the same moisture content, indicating that both the feedstock type and the moisture content influence the methane emissions.

All biomasses with moisture contents above 25% (e.g., reed, coffee stem wood, guadua, or wheat straw with moisture contents of 39%, 26%, 27%, 26%, respectively) showed significantly higher methane emission factors between 30 and 40 kg per ton of biochar (Figure 1, Table 2).

The relationship between higher moisture contents in feedstock and higher methane emission factors was observed across all five feedstocks tested. However, the interaction between feedstock and moisture content also had an important impact on methane emission factors. Therefore, a prediction of the methane emission factors based solely on the moisture content is not always possible.

The influence of the flue gas temperature on the CH_4 emission factors was also tested (Figure 2). While the kiln or flue gas temperature assessment can be successfully used to record valuable data, like kiln runtimes and estimated biochar production, it is not sufficiently reliable to estimate methane emission factors over a wide range of feedstocks. Here we found that the temperature itself is also impacted by kiln size, kiln management, and feedstock characteristics such as mass, calorific value, and bulkiness. These factors would need to be considered in order to define relationships between kiln temperature and methane emissions.

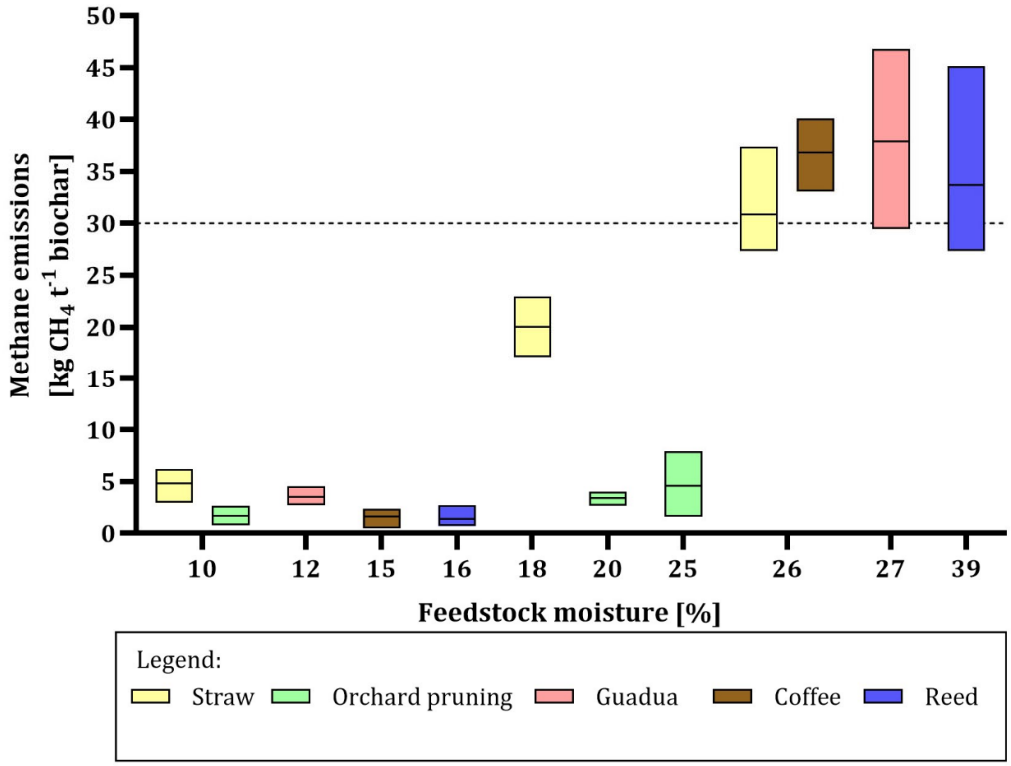

Figure 1: Methane emission factors for Kon-Tiki Pyrolysis of different feedstocks and different feedstock moisture contents, given in [%]. Dotted horizontal line represent the 30 kg t^{-1} biochar emission factor applied in the Global Artisan C-Sink Standard (CSI 2024). Boxes range from min to max, with the central line indicating the arithmetic mean.

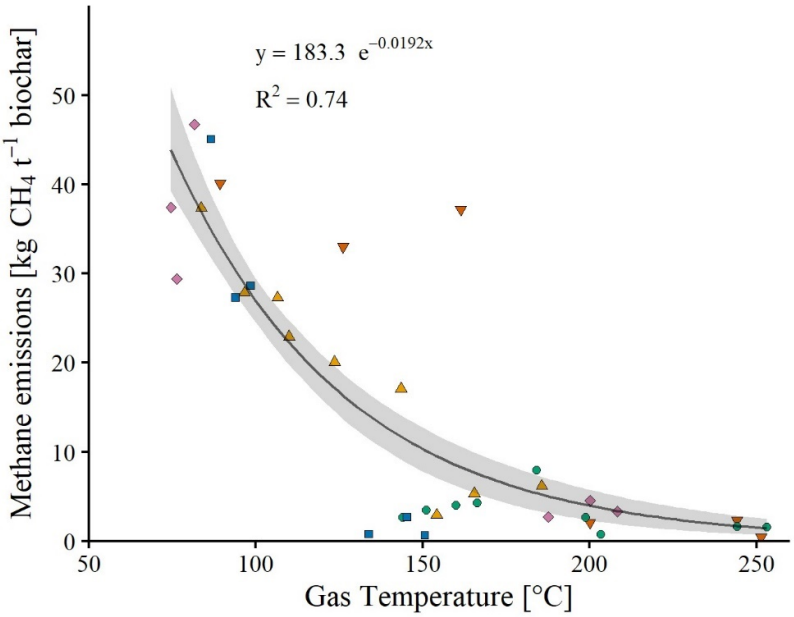

Figure 2: Impact of the flue gas temperature on flame curtain pyrolysis methane emission factors (kg CH_4 t^{-1} biochar). Feedstocks are depicted with varying symbols as data points: wheat straw: yellow triangles; orchard pruning: green dots, guadua: pink rhombs, coffee: orange down-pointing triangles; reed: blue squares. Black lines represent the model prediction; the gray band represents the confidence interval (95%).

4.2 Feedstock moisture

Our data confirm the strong relationship between feedstock moisture and Kon-Tiki methane emissions. This general relationship was already claimed by Cornelissen et al. (2023; 2024), and our measurement campaign adds further insights. As long as the craft of the artisan ensures timely layering of the feedstock, feedstock moisture is the most suitable predictor for methane emissions. However, we also showed that the moisture content is not the only factor decisive for the emission factors, as the class of feedstock type further influences emission factors.

4.3 Feedstock type

In addition to moisture content, the type of feedstock plays a significant role in determining methane emissions during Kon-Tiki pyrolysis. Within our dataset, woody biomass typically presents low methane emission factors, given that moisture levels were below 25%. However, straw-type feedstocks require special attention. Our measurements show that even at relatively low moisture levels (18%) straw can produce substantial methane emissions (20 kg CH_4 t^{-1} biochar). Therefore, the low emission factor of 5 kg CH_4 t^{-1} biochar was only observed for dry straws (< 15 % moisture).

Lastly, feedstock particle size must also be considered: fine-grained material with particle diameters of 2–3 cm should be avoided altogether, as such material tends to prevent proper airflow and layering, which increases the risk of incomplete combustion and elevated methane emissions (Cornelissen et al. 2024).

4.4 Temperature

The gas temperature and the kiln temperature were tested as potential indicators for Kon-Tiki methane emission factors. We could show that the gas temperature is a valuable predictor of pyrolysis quality and, thus, emissions. However, the kiln temperature not only depends on feedstock humidity and artisanal craft but also on kiln size and geometry, pyrolysis duration, and feedstock type. Within our extensive dataset, it occurred that methane emission factors varied while the recorded temperatures did not, and vice versa. For reed, wheat straw, and guadua, a significant regression for kiln temperature and CH_4 emission factor could be established. However, for coffee stem wood and orchard pruning, no significant relationship was found. Nevertheless, temperature logging offers the practical advantage of real-time monitoring throughout the entire pyrolysis process. Gas temperature can serve as an important proxy for methane emission control, provided that kiln type and feedstock are accounted for and temperature thresholds are calibrated for each kiln-feedstock combination. Once established, continuous temperature monitoring offers a promising pathway toward simplified, field-deployable emission proxy monitoring for artisan biochar production systems.

4.5 Emission comparison of Kon-Tiki to open field burning

CO and CH_4 emissions were on average lower in the Kon-Tiki than in the respective open burning event.

To compare Kon-Tiki emissions with those from open burning, the emission factors for CO_2, CO and CH_4 are given in kg per t feedstock (dry weight). Despite large

variability, CO_2 emission factors from Kon-Tikis are lower by an average of 20% for all feedstocks and moisture categories compared to the same feedstock under open burning. Similarly, CO emission factors were on average 19 kg lower for Kon-Tiki pyrolysis (representing a decrease of 35%). Regarding methane emission factors per ton of feedstock, values were on average 36% (1.4 kg CH_4 t^{-1} feedstock) lower for the Kon-Tiki compared to the respective open burning (Figure 3, Table 2). Notably, methane emission factors were very low (≤ 1 kg CH_4 t^{-1} feedstock) for both open burning and Kon-Tiki for woody feedstocks under 30% moisture content, while they were significantly lower in the Kon-Tiki for wheat straw, irrespective of the moisture content.

Methane emission factors increased with feedstock moisture content. This pattern can be observed for Kon-Tiki pyrolysis and open field burning (Figure 1, Figure 3). Directly comparing methane emissions for same feedstock characteristics, mean CH_4 emission factors were similar or higher for open burning throughout all feedstocks and moisture categories tested (Figure 3, Table 2). For straw, a crop residue commonly burnt, emission factors were always higher for open burning.

The measured emission factors varied greatly, depending on the feedstock type and the moisture content. CO and CH_4, emission factors for wheat straw were generally above-average (Table 2). The burning of wheat straw with 26% moisture content caused the highest CH_4 emissions, yet this value was within the range of comparable literature values (Arai et al. 2015). Overall, a good agreement between literature values and emission factors established in this study was found.

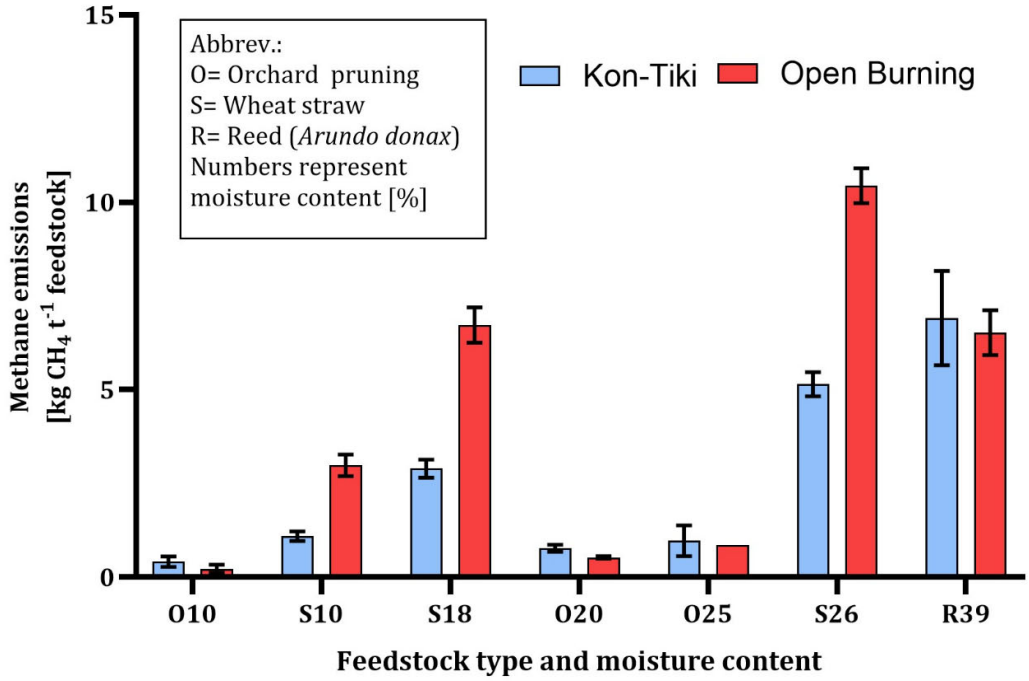

Figure 3: Barplot comparison of mean methane emission factors in kg per ton dry feedstock between Kon-Tiki pyrolysis and open field burning. The numbers after the capital letter represent feedstock moisture content, e.g., S18= Wheat straw with 18% moisture content. Error bars show the standard error of the mean (n=3, for all bars, except open burning at O25, here n=1, hence no error bar is shown).

Table 2: Overview of carbonaceous gas concentrations in the flue gas, resulting emission factors per ton of feedstock (on dry weight basis) and per ton of biochar produced (on dry weight basis). Values are reported as mean ± standard deviation (n=3, except Open Burning of orchard pruning with 25% moisture content), dw=dry weight, FS= feedstock, BC=biochar.

	Feedstock	Water cont. %	Mean gas concentration			Emission factors in kg t^{-1} feedstock (dw)			Emission factors in kg t^{-1} biochar (dw)			Biochar yield %
			mol% CO2	mol% CO	mol% CH4	CO2 kg t^{-1} FS (dw)	CO kg t^{-1} FS (dw)	CH4 kg t-1 FS (dw)	CO2 kg t^{-1} BC (dw)	CO kg t^{-1} BC (dw)	CH4 kg t^{-1} BC (dw)	
Kon-Tiki	Wheat Straw	10	96.75 ± 0.39	2.88 ± 0.36	0.28 ± 0.03	1052 ± 108	20.0 ± 3.5	1.1 ± 0.2	4579 ± 1335	86.8 ± 26.2	4.8 ± 1.7	23.9 ± 4.8
	Wheat Straw	18	93.44 ± 0.91	5.80 ± 0.83	0.60 ± 0.09	1247 ± 8	49.3 ± 7.3	2.9 ± 0.4	8613 ± 264	341.2 ± 59.2	20.0 ± 2.9	14.5 ± 0.5
	Wheat Straw	26	89.70 ± 1.01	8.88 ± 0.88	1.09 ± 0.10	1159 ± 28	73.1 ± 8.2	5.2 ± 0.6	6910 ± 648	437.4 ± 80.2	30.8 ± 5.7	16.9 ± 1.2
	Orchard pruning	10	98.60 ± 0.71	1.26 ± 0.63	0.11 ± 0.06	1017 ± 7	8.3 ± 4.2	0.4 ± 0.2	4131 ± 73	33.7 ± 16.8	1.7 ± 0.9	24.6 ± 0.3
	Orchard pruning	20	97.25 ± 0.36	2.50 ± 0.32	0.19 ± 0.04	1076 ± 14	17.6 ± 2.2	0.8 ± 0.2	4699 ± 142	76.8 ± 8.3	3.4 ± 0.7	22.9 ± 0.4
	Orchard pruning	25	97.43 ± 1.41	2.30 ± 1.24	0.23 ± 0.17	1154 ± 40	17.3 ± 9.2	1.0 ± 0.7	5491 ± 380	82.0 ± 43.3	4.6 ± 3.2	21.1 ± 0.9
	Reed	16	98.33 ± 0.82	1.58 ± 0.76	0.06 ± 0.05	1171 ± 51	12.1 ± 6.3	0.3 ± 0.2	5667 ± 708	60.1 ± 35.2	1.4 ± 1.1	20.8 ± 1.8
	Reed	39	89.88 ± 1.70	8.37 ± 1.13	1.55 ± 0.51	1105 ± 35	65.4 ± 8.0	6.9 ± 2.2	5411 ± 273	319.6 ± 32.5	33.7 ± 9.9	20.4 ± 0.4
	Coffee	15	98.83 ± 0.22	1.06 ± 0.18	0.07 ± 0.05	1170 ± 11	8.0 ± 1.4	0.3 ± 0.2	5796 ± 187	39.8 ± 7.8	1.6 ± 1.0	20.2 ± 0.5
	Coffee	26	92.04 ± 0.45	6.22 ± 0.52	1.56 ± 0.09	1129 ± 14	48.5 ± 3.8	7.0 ± 0.5	5930 ± 265	254.6 ± 16.7	36.8 ± 3.6	19.1 ± 0.6
	Guadua	12	97.89 ± 0.17	1.92 ± 0.16	0.15 ± 0.03	1221 ± 42	15.3 ± 1.7	0.7 ± 0.1	6421 ± 596	80.4 ± 12.5	3.5 ± 0.9	19.1 ± 1.2
	Guadua	27	90.50 ± 0.36	7.96 ± 0.50	1.29 ± 0.16	1206 ± 37	67.4 ± 2.7	6.3 ± 0.9	7206 ± 814	401.6 ± 24.6	37.8 ± 8.7	16.8 ± 1.4
Open field burning	Wheat Straw	10	94.20 ± 0.88	5.11 ± 0.80	0.53 ± 0.09	1447 ± 13	50.0 ± 8.6	3.0 ± 0.5				
	Wheat Straw	18	89.85 ± 0.64	8.61 ± 0.47	1.19 ± 0.13	1394 ± 5	85.1 ± 5.6	6.7 ± 0.8				
	Wheat Straw	26	86.02 ± 1.11	11.60 ± 0.94	1.84 ± 0.15	1342 ± 22	115.1 ± 8.9	10.4 ± 0.8				
	Orchard pruning	10	98.41 ± 0.32	1.52 ± 0.27	0.04 ± 0.04	1350 ± 21	13.3 ± 2.2	0.2 ± 0.2				
	Orchard pruning	20	97.67 ± 0.23	2.18 ± 0.23	0.10 ± 0.01	1399 ± 8	19.8 ± 2.1	0.5 ± 0.1				
	Orchard pruning	25	97.35 ± n.d.	2.46 ± n.d.	0.16 ± n.d	1430 ± n.d.	23.0 ± n.d.	0.9 ± n.d.				
	Reed	39	90.69 ± 0.94	7.99 ± 0.71	1.15 ± 0.22	1420 ± 60	79.5 ± 4.4	6.5 ± 1.0				

5. Possibilities of CH_4-reduction in Kon-Tiki biochar production

The measurement campaign on methane emissions from Kon-Tiki pyrolysis shed light on parameters that influence the emission factors. Within the range of suitable feedstocks, the moisture content is the most important indicator, influencing the performance of the Kon-Tiki. A continuous flame curtain, the guiding principle of Kon-Tiki pyrolysis, can hardly be achieved with a feedstock moisture content above 25%. With moisture contents below 25%, a good flame consistency can be achieved, leading to a combustion of the pyrolysis gases and formation of higher shares of CO_2, compared to CO and CH_4. Hence, emission factors for CH_4 from low moisture feedstocks were always below the generic emission factor of 30 kg t^{-1} biochar, and even below 5 kg CH_4 t^{-1} biochar for woody biomass.

Depending on the feedstock moisture content, Kon-Tiki emission factors for Artisan biochar production could be redefined:

- For dry feedstocks with moisture contents below 15%, a methane emission factor of 5 kg CH_4 t^{-1} is realistic and still conservative.
- For semi-moist feedstocks with moisture contents between 15% and 25%, a generic emission factor of 20 kg CH_4 t^{-1} could be applied.
- All feedstocks with moisture content above 25% are not regarded suitable for artisanal biochar production with the Kon-Tiki.

While semi-moist wheat straw showed higher emissions compared to woody biomasses, these emissions were still below the emissions occurring during open field burning of the same straw. Therefore, if open field burning is avoided and Kon-Tiki biochar production is adopted, significantly less methane will be emitted when compared to the baseline scenario. We recommend pre-drying low-lignin and high-cellulose feedstock types to a moisture content below 15%, to assure low methane emissions.

Flue gas temperature logging may also become an important monitoring tool to ensure low methane emissions. However, specific temperature thresholds need to be calibrated to specific kiln/feedstock combinations. Exemplarily, based on our data, three indicative emission classes could be proposed with flue gas temperature being measured inside the stack channeling the Kon-Tiki combustion gases above the kiln (see chapter 6.3 and Figure 2):

(I) Flue gas temperature > 190 °C, corresponding to emission factors < 5 kg CH_4 t^{-1} biochar;
(II) Flue gas temperature between 131 °C and 190 °C, corresponding to emission factors < 15 kg CH_4 t^{-1} biochar; and
(III) Flue gas temperature between 95 °C and 130 °C, corresponding to emission factors < 30 kg CH_4 t^{-1} biochar.

6. Monitoring methods/procedures that guarantee low CH_4 emissions

6.1 Direct measurements of feedstock moisture

While we show here that the feedstock moisture has a large impact on methane emission factors from flame curtain pyrolysis, reliable assessment of the feedstock moisture content in the field can be challenging. There are direct and indirect methods to assess the feedstock moisture content for Artisan biochar production.

Direct measurements to assess the feedstock moisture content prior to pyrolysis involve:

(a) pin-type moisture meters that measure electrical resistance of the feedstock and can be calibrated for many kinds of biomasses.

(b) infrared devices

(c) high temperature moisture analyzers equipped with weighing scales that assess weight loss during drying.

Each of the above-mentioned methods has its advantages and limitations. Pin-type moisture meters (a) allow rapid in-field readings without sample preparation. However, accurate results are only achievable if the instrument carries a validated, species-specific calibration curve for the wood type being measured. Infrared devices (b) measure the near surface moisture of a biomass particle, hence these devices are not suitable for thicker feedstock pieces commonly used in Kon-Tiki pyrolysis. While for smaller branches, twigs, or corn cobs, the superficial moisture is representative also for the core moisture, for wood logs or bamboo poles, the measured surface moisture varies greatly from the core moisture. Moisture analyzers (c) provide the most exact results, but require a lab-like set-up and may not be sturdy enough for Artisan feedstock moisture analysis. Despite these practical limitations, moisture analyzers remain the only option considered sufficiently reliable for certification purposes whenever pin-type meters are not applicable.

6.2 Indirect measurements of feedstock moisture

It was investigated if feedstock moisture content could be deduced from measuring the water vapor content in the flue gas. However, humidity measurement in the hot flue gas is challenging and expensive. Electronic hygrometers, which measure the change in resistance of material absorbing moisture from ambient air, cannot be applied in high-temperature flue gas environments with particulate matter (dust) and solvent gases, as these would quickly deteriorate the devices. The assessment via infrared is distorted by smoke and particulate matter generated in the process, which would reduce the reliability of such measurements. Another option would be a so-called psychrometric measurement, however, the high precision devices suitable for these challenging environments are too expensive (> 15.000 €) for the common Artisan use case.

Another possibility would be the assessment of the flame curtain stability via (RGB) cameras, which could provide direct insight into the CH_4 emissions. However, the set-up of visual live monitoring and recording of hundreds of farmers performing Kon-Tiki pyrolysis and the subsequent data analysis of these recordings is not realistic.

To summarize, no reliable and affordable indirect moisture measurements could be identified. We recommend direct measurements of the feedstock and assessment of the moisture content with pin-type moisture meters or moisture analyzers.

6.3 Gas temperature measurements

Flue gas temperature logging in decentralized biochar production systems can be implemented through low-cost, field-deployable IoT sensor networks. A thermocouple (typically Type-K) is positioned in the flue gas stream at a fixed, standardized location relative to the kiln geometry. The thermocouple is connected to a microcontroller unit, which reads temperature at defined intervals (e.g., every 30 seconds) and transmits data wirelessly.

In areas with mobile network coverage, data can be transmitted in real time via GSM or 4G modules to a cloud-based data platform, where it can be stored and monitored remotely.

The resulting continuous temperature log provides a timestamped record of the entire pyrolysis cycle, which can be used to assign each production batch to a methane emission factor class.

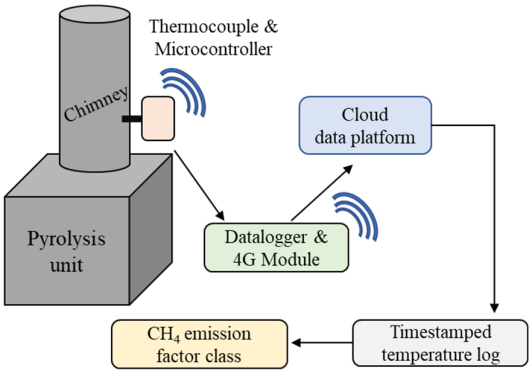

Figure 4: Schematic overview of a low-cost temperature sensor system for flue gas temperature monitoring in decentralized biochar production. A Type-K thermocouple logs flue gas temperatures; data are transmitted via 4G to a cloud platform and used to classify CH_4 emission factors per production batch.

7. CH_4 avoidance and offset

Here, we present, to our knowledge, the first published dataset, that directly compares emissions from pile-type open crop residue burning and Kon-Tiki pyrolysis. Our emission assessment from both processes shows that Kon-Tiki type pyrolysis produces less methane emissions than open crop waste burning. We showed that compared to open burning as baseline scenario, GHG and CO emissions are reduced when transforming crop waste into biochar using Kon-Tiki pyrolysis. If the production of biochar from crop waste replaces crop waste burning, it may declare the avoidance of crop waste burning emissions. The Kon-Tiki methane emissions must still be accounted for in the GHG balance, but the project's overall climate benefit could be determined by the avoidance of the significantly higher emissions from open burning.

However, justifying Kon-Tiki pyrolysis emissions solely by avoiding even larger open burning emissions cannot be the long-term solution. Ultimately, GHG emissions from Kon-Tiki pyrolysis have to be offset with carbon sinks of corresponding persistence. In the Global Artisan C-Sink (CSI, 2024), a ten-year validity for the avoidance of the emissions from the baseline scenario (open crop burning) is granted; thereafter, emissions have to be offset with corresponding carbon sinks.

Due to the limited lifetime of methane in the atmosphere (< 20 years), an offsetting carbon sink may have a carbon sequestration cycle of only 20 years. The semi-persistent carbon (SPC) fraction of biochar (25% of a biochar with a H/C_{org} ratio < 0.4), which is defined as the biochar-carbon fraction that is expected to decay within the first 1000 years, could be used to offset the climate warming effect of methane emissions. Also, the accumulated carbon captured by tree growth over 20 years could be used as a temporary C-Sink to offset the equally temporary climate warming effect of methane emissions.

8. Recommendations for Global Artisan C-Sink producers

Efficient drying of feedstock is essential to minimize methane emissions. Biomass should be protected from rain by storage under shelters or tarpaulins, while maintaining sufficient airflow to enhance drying. For larger woody feedstocks, stockpiles can be arranged to ensure adequate ventilation and to keep the material raised above the ground. For straw-like or loose feedstocks, drying over a larger surface area, such as a field or concrete pad, is preferred. Where possible, C-Sink producers are encouraged to employ waste heat from pyrolysis to accelerate and overall improve the drying process.

Monitoring and control of feedstock moisture is equally important. High-quality moisture analyzers that function on the loss on drying principle or specifically calibrated and periodically validated moisture meters are required for this purpose. Dried feedstock must be protected from rewetting during storage. Consistent moisture thresholds, e.g., < 15% moisture content, must be defined by standards to claim dry feedstock for low emissions.

Real-time gas temperature monitoring can be considered a suitable alternative to moisture content analysis to ensure low methane emissions. Additional data is required to define device specific temperature thresholds which can be adequately and robustly linked to low methane emissions.

9. References

Akagi, S. K.; Yokelson, R. J.; Wiedinmyer, C.; Alvarado, M. J.; Reid, J. S.; Karl, T. et al. (2011): Emission factors for open and domestic biomass burning for use in atmospheric models. In *Atmos. Chem. Phys.* 11 (9), pp. 4039–4072. DOI: 10.5194/acp-11-4039-2011.

Andreae, M. O.; Merlet, P. (2001): Emission of trace gases and aerosols from biomass burning. In *Global Biogeochemical Cycles* 15 (4), pp. 955–966. DOI: 10.1029/2000GB001382.

Andreae, Meinrat O. (2019): Emission of trace gases and aerosols from biomass burning – an updated assessment. In *Atmos. Chem. Phys.* 19 (13), pp. 8523–8546. DOI: 10.5194/acp-19-8523-2019.

Arai, Hironori; Hosen, Yasukazu; van Pham Hong, Nguyen; Thi, Nga Truong; Huu, Chiem Nguyen; Inubushi, Kazuyuki (2015): Greenhouse gas emissions from rice straw burning and straw-mushroom cultivation in a triple rice cropping system in the Mekong Delta. In *Soil Science and Plant Nutrition* 61 (4), pp. 719–735. DOI: 10.1080/00380768.2015.1041862.

Aurell, Johanna; Gullett, Brian K.; Tabor, Dennis; Yonker, Nick (2017): Emissions from prescribed burning of timber slash piles in Oregon. In *Atmospheric Environment* 150, pp. 395–406. DOI: 10.1016/j.atmosenv.2016.11.034.

Balcombe, Paul; Speirs, Jamie F.; Brandon, Nigel P.; Hawkes, Adam D. (2018): Methane emissions: choosing the right climate metric and time horizon. In *Environ. Sci.: Processes Impacts* 20 (10), pp. 1323–1339. DOI: 10.1039/C8EM00414E.

Chouchene, Ajmia; Jeguirim, Mejdi; Khiari, Besma; Trouvé, Gwenaelle; Zagrouba, Féthi (2010): Study on the emission mechanism during devolatilization/char oxidation and direct oxidation of olive solid waste in a fixed bed reactor. In *Journal of Analytical and Applied Pyrolysis* 87 (1), pp. 168–174. DOI: 10.1016/j.jaap.2009.11.008.

Christian, T. J.; Kleiss, B.; Yokelson, R. J.; Holzinger, R.; Crutzen, P. J.; Hao, W. M. et al. (2003): Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels. In *J. Geophys. Res.* 108 (D23), Article 2003JD003704. DOI: 10.1029/2003JD003704.

Collins, William J.; Webber, Christopher P.; Cox, Peter M.; Huntingford, Chris; Lowe, Jason; Sitch, Stephen et al. (2018): Increased importance of methane reduction for a 1.5 degree target. In *Environ. Res. Lett.* 13 (5), p. 54003. DOI: 10.1088/1748-9326/aab89c.

Cornelissen, Gerard; Makate, Clifton; Mulder, Jan; Janssen, Jente; Trimarco, Jon; Obia, Alfred et al. (2024): Emission Factors for Biochar Production from Various Biomass Types in Flame Curtain Kilns. In *Applied Sciences* 14 (21), p. 9649. DOI: 10.3390/app14219649.

Cornelissen, Gerard; Pandit, Naba Raj; Taylor, Paul; Pandit, Bishnu Hari; Sparrevik, Magnus; Schmidt, Hans Peter (2016): Emissions and Char Quality of Flame-Curtain "Kon Tiki" Kilns for Farmer-Scale Charcoal/Biochar Production. In *PLOS ONE* 11 (5), e0154617. DOI: 10.1371/journal.pone.0154617.

Cornelissen, Gerard; Sørmo, Erlend; La Rosa, Ruy Korscha Anaya de; Ladd, Brenton (2023): Flame curtain kilns produce biochar from dry biomass with minimal methane emissions. In *The Science of the total environment* 903, p. 166547. DOI: 10.1016/j.scitotenv.2023.166547.

CSI (2024): Global Artisan C-Sink. Guidelines for Carbon Sink Certification for artisan biochar production. Version 2.1A. In *Carbon Standards International AG*. Available online at https://www.carbon-standards.com/docs/transfer/4000136EN.pdf.

Estrellan, Carl Renan; Iino, Fukuya (2010): Toxic emissions from open burning. In *Chemosphere* 80 (3), pp. 193–207. DOI: 10.1016/j.chemosphere.2010.03.057.

Etminan, M.; Myhre, G.; Highwood, E. J.; Shine, K. P. (2016): Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. In *Geophysical Research Letters* 43 (24), 12,614-12,623. DOI: 10.1002/2016GL071930.

Forster, P.; T. Storelvmo; K. Armour; W. Collins; J.-L. Dufresne; D. Frame et al. (2021): The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 923–1054. DOI: 10.1017/9781009157896.009.

Gadde, Butchaiah; Bonnet, Sébastien; Menke, Christoph; Garivait, Savitri (2009): Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. In *Environmental pollution (Barking, Essex : 1987)* 157 (5), pp. 1554–1558. DOI: 10.1016/j.envpol.2009.01.004.

Hayashi, Kentaro; Ono, Keisuke; Kajiura, Masako; Sudo, Shigeto; Yonemura, Seiichiro; Fushimi, Akihiro et al. (2014): Trace gas and particle emissions from open burning of three cereal crop residues: Increase in residue moistness enhances emissions of carbon monoxide, methane, and particulate organic carbon. In *Atmospheric Environment* 95, pp. 36–44. DOI: 10.1016/j.atmosenv.2014.06.023.

Jackson, R. B.; Saunois, M.; Bousquet, P.; Canadell, J. G.; Poulter, B.; Stavert, A. R. et al. (2020): Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. In *Environ. Res. Lett.* 15 (7), p. 71002. DOI: 10.1088/1748-9326/ab9ed2.

Jeltsch-Thömmes, Aurich; Joos, Fortunat (2019): The response to pulse-like perturbations in atmospheric carbon and carbon isotopes.

Koppmann, R.; Czapiewski, K. von; Reid, J. S. (2005): A review of biomass burning emissions, part I: gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds. In *Atmospheric Chemistry and Physics Discussions* 5 (5), pp. 10455–10516. DOI: 10.5194/acpd-5-10455-2005.

Li, Xinghua; Wang, Shuxiao; Duan, Lei; Hao, Jiming; Li, Chao; Chen, Yaosheng; Yang, Liu (2007): Particulate and trace gas emissions from open burning of wheat straw and corn stover in China. In *Environmental Science & Technology* 41 (17), pp. 6052–6058. DOI: 10.1021/es0705137.

McMeeking, Gavin R.; Kreidenweis, Sonia M.; Baker, Stephen; Carrico, Christian M.; Chow, Judith C.; Collett, Jeffrey L. et al. (2009): Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory. In *J. Geophys. Res.* 114 (D19), Article 2009JD011836. DOI: 10.1029/2009JD011836.

Melo, Leônidas Carrijo Azevedo; Lehmann, Johannes; Da Carneiro, Jefferson Santana Silva; Camps-Arbestain, Marta (2022): Biochar-based fertilizer effects on crop productivity: a meta-analysis. In *Plant Soil* 472 (1-2), pp. 45–58. DOI: 10.1007/s11104-021-05276-2.

Miura, Yoshinori; Kanno, Tadanori (1997): Emissions of trace gases (CO 2, CO, CH 4, and N 2 O) resulting from rice straw burning. In *Soil Science and Plant Nutrition* 43 (4), pp. 849–854. DOI: 10.1080/00380768.1997.10414651.

Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J. et al. (2013): Anthropogenic and Natural Radiative Forcing. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Cambridge University Press*.

Nussbaumer, Thomas (2003): Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction. In *Energy Fuels* 17 (6), pp. 1510–1521. DOI: 10.1021/ef030031q.

Oanh, Nguyen Thi Kim; Bich, Thuy Ly; Tipayarom, Danutawat; Manadhar, Bhai R.; Prapat, Pongkiatkul; Simpson, Christopher D.; Liu, L-J Sally (2011): CHARACTERIZATION OF PARTICULATE MATTER EMISSION FROM OPEN BURNING OF RICE STRAW. In *Atmospheric Environment* 45 (2), pp. 493–502. DOI: 10.1016/j.atmosenv.2010.09.023.

Pennise, David M.; Smith, Kirk R.; Kithinji, Jacob P.; Rezende, Maria Emilia; Raad, Tulio Jardim; Zhang, Junfeng; Fan, Chengwei (2001): Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. In *J. Geophys. Res.* 106 (D20), pp. 24143–24155. DOI: 10.1029/2000JD000041.

Price-Allison, A.; Lea-Langton, A. R.; Mitchell, E.J.S.; Gudka, B.; Jones, J. M.; Mason, P. E.; Williams, A. (2019): Emissions performance of high moisture wood fuels burned in a residential stove. In *Fuel* 239, pp. 1038–1045. DOI: 10.1016/j.fuel.2018.11.090.

Price-Allison, Andrew; Mason, Patrick E.; Jones, Jenny M.; Barimah, Eric K.; Jose, Gin; Brown, Aaron E. et al. (2023): The Impact of Fuelwood Moisture Content on the Emission of Gaseous and Particulate Pollutants from a Wood Stove. In *Combustion Science and Technology* 195 (1), pp. 133–152. DOI: 10.1080/00102202.2021.1938559.

Sahai, Shivraj; Sharma, C.; Singh, D. P.; Dixit, C. K.; Singh, Nahar; Sharma, P. et al. (2007): A study for development of emission factors for trace gases and carbonaceous particulate species from in situ burning of wheat straw in agricultural fields in india. In *Atmospheric Environment* 41 (39), pp. 9173–9186. DOI: 10.1016/j.atmosenv.2007.07.054.

Saunois, Marielle; Stavert, Ann R.; Poulter, Ben; Bousquet, Philippe; Canadell, Josep G.; Jackson, Robert B. et al. (2020): The Global Methane Budget 2000–2017. In *Earth Syst. Sci. Data* 12 (3), pp. 1561–1623. DOI: 10.5194/essd-12-1561-2020.

Schmidt, H.-P.; Taylor, Paul (2014): Kon-Tiki flame cap pyrolysis for the democratization of biochar production (1). Available online at https://www.researchgate.net/publication/275097537_Kon-Tiki_flame_cap_pyrolysis_for_the_democratization_of_biochar_production.

Schmidt, Hans-Peter; Kammann, Claudia; Hagemann, Nikolas; Leifeld, Jens; Bucheli, Thomas D.; Sánchez Monedero, Miguel Angel; Cayuela, Maria Luz (2021): Biochar in agriculture – A systematic review of 26 global meta-analyses. In *GCB Bioenergy* 13 (11), pp. 1708–1730. DOI: 10.1111/gcbb.12889.

Sparrevik, Magnus; Adam, Chris; Martinsen, Vegard; Jubaedah; Cornelissen, Gerard (2015): Emissions of gases and particles from charcoal/biochar production in rural areas using medium-sized traditional and improved "retort" kilns. In *Biomass and Bioenergy* 72, pp. 65–73. DOI: 10.1016/j.biombioe.2014.11.016.

Springsteen, Bruce; Christofk, Thomas; York, Robert A.; Mason, Tad; Baker, Stephen; Lincoln, Emily et al. (2015): Forest biomass diversion in the Sierra Nevada: Energy, economics and emissions. In *Cal Ag* 69 (3), pp. 142–149. DOI: 10.3733/ca.v069n03p142.

Stockwell, C. E.; Yokelson, R. J.; Kreidenweis, S. M.; Robinson, A. L.; DeMott, P. J.; Sullivan, R. C. et al. (2014): Trace gas emissions from combustion of peat, crop residue, domestic biofuels, grasses, and other fuels: configuration and Fourier transform infrared (FTIR) component of the fourth Fire Lab at Missoula Experiment (FLAME-4). In *Atmos. Chem. Phys.* 14 (18), pp. 9727–9754. DOI: 10.5194/acp-14-9727-2014.

Tazebew, Ewunetu; Addisu, Solomon; Bekele, Eshetu; Alemu, Asmamaw; Belay, Berhanu; Sato, Shinjiro (2024): Enhancing wood to charcoal conversion efficiencies from smallholder plantation charcoal production systems: Implications for carbon emissions and sustainable livelihood benefits in North Western Ethiopia. In *Environ Monit Assess* 196 (2), p. 162. DOI: 10.1007/s10661-024-12354-2.

UNEP, CCAC (2021): Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. In *United Nations Environment Programme, Climate and Clean Air Coalition*.

Vakkilainen, Esa Kari (2017): Steam generation from biomass : construction and design of large boilers. Construction and Design of Large Boilers: Butterworth-Heinemann.

Wang, Hongli; Lou, Shengrong; Huang, Cheng; Qiao, Liping; Tang, Xibin; Chen, Changhong et al. (2014): Source Profiles of Volatile Organic Compounds from Biomass Burning in Yangtze River Delta, China. In *Aerosol Air Qual. Res.* 14 (3), pp. 818–828. DOI: 10.4209/aaqr.2013.05.0174.

Ward, D. E.; Sandberg, D. V.; Ottmar, R. D.; Anderson, J. A.; Hofner, G. G.; Fitzsimmons, C. K. (1982): Measurements of smokes from two prescribed fires in the Pacific Northwest. Available online at https://scholar.google.com/citations?user=guposwoaaaaj&hl=en&oi=sra.

Ye, Lili; Camps-Arbestain, Marta; Shen, Qinhua; Lehmann, Johannes; Singh, Balwant; Sabir, Muhammad (2020): Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. In *Soil Use and Management* 36 (1), pp. 2–18. DOI: 10.1111/sum.12546.

Yokelson, R. J.; Burling, I. R.; Urbanski, S. P.; Atlas, E. L.; Adachi, K.; Buseck, P. R. et al. (2011): Trace gas and particle emissions from open biomass burning in Mexico. In *Atmos. Chem. Phys.* 11 (14), pp. 6787–6808. DOI: 10.5194/acp-11-6787-2011.

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Methods: Principles of methane emission tests above the Kon-Tiki

Experimental set-up

Supplementary Figure 1: Illustration of the small (left) and mid-size (right) metal Kon-Tiki with the hood and chimney for emission assessment.

Flame curtain pyrolysis is an open pyrolysis process. For the waste gas emissions measurements, a metal hood and chimney were placed above the kilns (Supplementary Figure 1). This set-up facilitated channeling the gas into the chimney, where gas concentration measurements were performed. For wheat straw, orchard pruning, and giant reed, a 150 L Kon-Tiki was used. For guadua and coffee stem wood a 1000 L Kon-Tiki was used (Supplementary Figure 1). Flame curtain pyrolysis and open burning runs for wheat straw, orchard pruning, and giant reed were performed in Raimat, Lleida, Spain, between February and May 2025 on sunny days with no to little wind. Flame curtain pyrolysis runs for guadua bamboo and coffee stem wood were carried out in Pitalito and Zipacón, Colombia under a roof on calm days (wind < 5 km/h).

Open burning

For the open burning the equal mass of feedstock used for pyrolysis (dry weight basis) was piled up loosely under the hood and ignited from the bottom (Supplementary Figure 2). Three replications were carried out per moisture category per feedstock type. Yielding three measurements of gas emissions for open burning per feedstock type per moisture level, except for the highest moisture content (25%) of orchard pruning (n=1). Open field burning flue gas analysis was stopped once waste gas amounts were declining towards the limit of detection of the gas emissions measurement device. Hence, flaming combustion and char oxidation were recorded until the feedstock had turned into a pile of char/ashes waste gas amounts declined significantly.

Supplementary Figure 2: Illustration of the open burning events of pile-up biomass under the hood and chimney for waste gas analysis.

Gas emission measurement

Gas emissions were measured during the whole pyrolysis and open burning events, with a MRU MGAprime (MRU GmbH, Neckarsulm, Germany). The MGAprime was calibrated by Kull Instruments (Reiden, Switzerland) and is equipped with NDIR Sensors (CO_2, CO, CH_4, C_3H_8) and a paramagnetic O_2 Sensor, all calibrated for the expected measurement

range. The device is verified and certified according to EN 15267 sheets 1, 2 and 4. Values were recorded every five seconds. The sampling probe was placed centrally, horizontally into the exhaust gas stream in the chimney (Supplementary Figure 3), approximately 1.5 m above the Kon-Tiki or feedstock pile. The sensors were zeroed and the probe was cleaned at the beginning of each measurement day.

Feedstock processing

We used wheat straw (*Triticum aestivum*, L.), annual fruit orchard pruning (*Prunus sp.*), giant reed (*Arundo donax*, L.), Guadua (*Guadua angustifolia*, Kunth) and coffee stem wood (*Coffea arabica*, L.) as feedstock for pyrolysis.

Wheat straw harvested one year earlier was sourced from local farmers. Fruit orchard pruning were sourced from local farmers shortly after pruning activity (January to March 2025, Raimat, Lleida). Guadua and coffee stem wood, were harvested then pyrolyzed in Colombia (Pitalito). Initial moisture content was analyzed and feedstock was left sun-drying to reach the respective moisture classes. Periodic measurement of moisture content was carried out to monitor the drying process. Immediately before pyrolysis and open burning, samples were taken to confirm the moisture content in the lab.

Moisture and carbon content

Per feedstock moisture category, five subsamples were taken via grab sampling, homogenized and dried with a PCE MA 110 TS (PCE GmbH, Meschde, Germany) moisture analyzer at 105 °C to determine moisture content. Biochar was also dried with the PCE MA 110 TS at 105 °C.

Temperature measurement

During the Kon-Tiki runs five Type K thermocouples (TC Direct, Mönchengladbach, Germany) were used for continuous temperature assessments. They were inserted in the upper wall of the Kon-Tiki maintaining similar distances to the edge (one in the center, two at 15 cm from the wall, two at 7.5 cm from wall).

Supplementary Figure 3: MRU MGAprime flue gas measurement analyzer with probe (left) and installation of the gas measurement probe in the flue gas stream (right).
Picture source: https://www.mru.eu/produkte/detail/mgaprime-q/

Supplementary Figure 4 : Installation and distribution of the Type K thermocouples in the Kon-Tiki kiln.

Carbon mass balance method

Flame curtain pyrolysis and open field burning were both taking place in an open environment. Given the nature of the processes and the experimental set-up with the flue gas hood, and the chimney, it is not feasible to prevent ambient air from mixing with the flue gas or channel 100% of the flue gases through the chimney and measure the absolute mass of emitted gases. We, therefore, used the carbon mass balance method (Ward et al. 1982; Koppmann et al. 2005; Cornelissen et al. 2016). Here, absolute feedstock dry weight and carbon content were measured to account for the carbon input. Likewise, absolute biochar or ash (for open field burning) dry weight and carbon content were assessed to account for the carbon output. The balance, subtracting carbon output from carbon input, is referred to as carbon loss, occurring in the form of carbonaceous gases and TSP. When assessing the emission ratios of CO_2, CO, and CH_4 in the flue gas, absolute mass can be calculated in relation to the above measured carbon loss. The carbon mass balance method is commonly used to calculate fire and pyrolysis emission factors (Ward et al., 1979; Ward and Radke, 1993, McMeeking et al., 2009, Cornelissen et al. 2016, Cornelissen et al. 2023). Here we, measured only the three most abundant carbonaceous flue gases (CO_2, CO and CH_4), all other carbonaceous flue gas compounds, e.g, NMVOC and TSP/PM were neglected as it has been shown that they only account for a minor part of the carbon emitted (Arai et al. 2015; Cornelissen et al. 2016). Nevertheless, this might lead to a slight overestimation of emission factors for CO_2, CO, and CH_4, as all other carbonaceous compounds are assumed to be zero in the flue gases assessment.

Kiln dimensions

Small:
Bottom diameter (green circle): 27 cm.
Top diameter (blue circle): 75 cm
Total height: 45 cm
Height of lower truncated cone: 20 cm
Height of upper cylinder: 25 cm
V=154 l

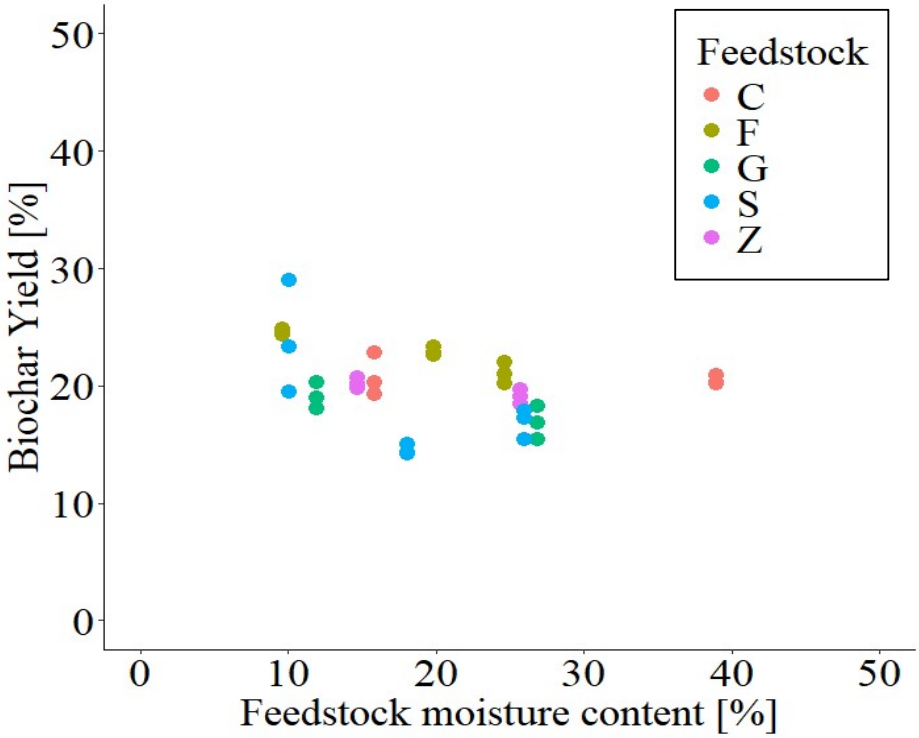
Large:
Bottom diameter: 82 cm.
Top diameter: 150 cm
Total height: 103 cm
V=1000 l

Further results

Supplementary Table 1: Overview of Kon-Tiki biochar production and open field burning runs with diverse feedstocks and feedstock moisture categories. Reporting biomass input water content, dry weight (dw), carbon mass input, biochar/char-ash output, carbon mass output. Carbon loss for carbon mass balance and biochar yield for the Kon-Tiki runs.
Values for output, carbon loss, and biochar yield are reported as mean ± standard deviation (n=3), except open burning orchard pruning with 25% moisture (n=1). For input, the standard deviation is 0, as same amounts were used for the three replicates.

	Feedstock	Water cont.	Input		Output		Carbon loss
		%	kg dw	kg C	kg dw	kg C	kg C
Kon-Tiki	Wheat Straw	10	9.7	4.4	2.3 ± 0.4	1.5 ± 0.2	2.9 ± 0.5
	Wheat Straw	18	9.9	4.5	1.4 ± 0.1	0.9 ± 0.0	3.6 ± 0.1
	Wheat Straw	26	9.4	4.3	1.6 ± 0.1	1.0 ± 0.1	3.3 ± 0.1
	Orchard pruning	10	21.3	10.4	5.3 ± 0.1	4.4 ± 0.1	6.0 ± 0.0
	Orchard pruning	20	21.2	10.4	4.9 ± 0.1	4.0 ± 0.1	6.4 ± 0.0
	Orchard pruning	25	20.7	10.1	4.3 ± 0.2	3.4 ± 0.1	6.7 ± 0.2
	Reed	16	18.9	9.0	3.9 ± 0.5	2.8 ± 0.4	6.2 ± 0.2
	Reed	39	19.6	9.3	4.0 ± 0.2	2.7 ± 0.2	6.6 ± 0.2
	Coffee	15	69.2	34.4	14.0 ± 1.0	12.1 ± 0.8	22.3 ± 0.8
	Coffee	26	48.2	24.0	9.2 ± 2.0	7.9 ± 1.7	16.1 ± 3.2
	Guadua	12	70.7	34.3	13.5 ± 2.2	10.3 ± 1.6	24.1 ± 4.1
	Guadua	27	17.2	8.4	2.8 ± 0.9	2.1 ± 0.6	6.3 ± 2.5
Open field burning	Wheat Straw	10	10.3	4.7	0.8 ± 0.1	0.4 ± 0.1	4.3 ± 0.0
	Wheat Straw	18	9.9	4.5	0.8 ± 0.0	0.3 ± 0.0	4.2 ± 0.1
	Wheat Straw	26	9.5	4.3	0.7 ± 0.0	0.3 ± 0.0	4.0 ± 0.3
	Orchard pruning	10	17.6	8.6	2.5 ± 0.3	2.0 ± 0.3	6.6 ± 1.1
	Orchard pruning	20	21.5	10.5	2.8 ± 0.1	2.1 ± 0.1	8.4 ± 0.3
	Orchard pruning	25	21.2	10.4	2.6 ± n.d	1.9 ± n.d	8.5 ± n.d
	Reed	39	19.8	9.4	2.0 ± 0.3	0.9 ± 0.3	8.5 ± 0.1

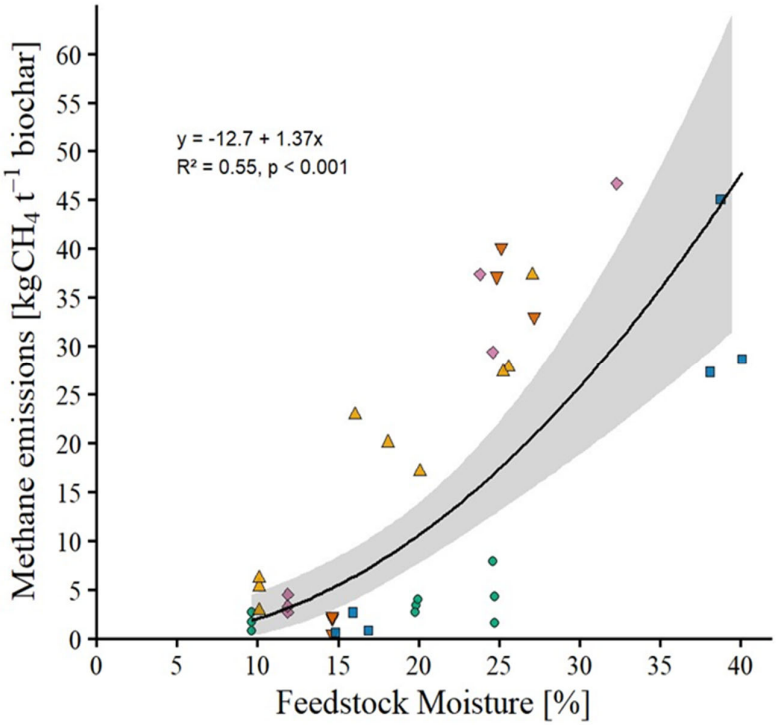
Kon-Tiki biochar yields



Supplementary Figure 5: Relationship between feedstock moisture content and biochar yield. Abbrev.: C= Reed, F= Fruit orchard pruning, G=Guadua, S=Wheat straw, Z= Coffee stem wood (Zoca).

There is a visible trend towards lower biochar yields with increasing moisture contents for all feedstocks, which reflects the increasing overlap of volatile and char combustion due to higher feedstock moisture contents. However, other factors, such as feedstock characteristics and the craftmanship of the biochar producer also play an important role in determining the biochar yield.

Feedstock moisture



Supplementary Figure 6: Regression between feedstock moisture content and methane emissions. Feedstock 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%).