

Original Research Report

Contribution of feedstock type to smokeless pyrolysis in flame curtain kilns

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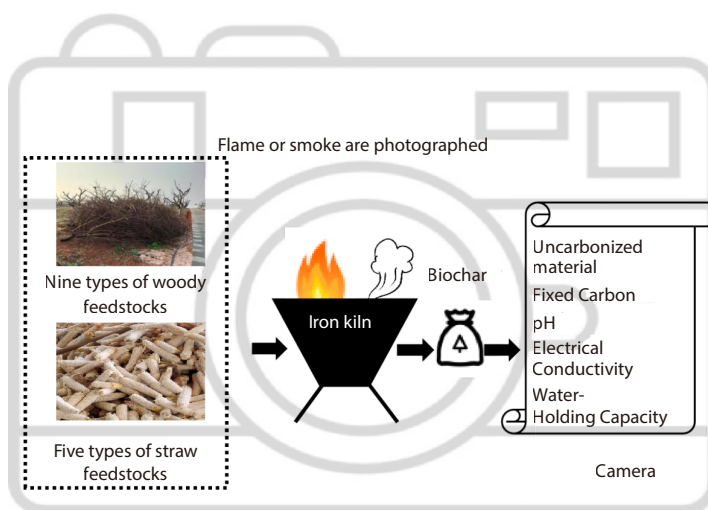
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Abstract: The smokeless performance of flame curtain pyrolysis kilns has been somewhat over-idealized. In this study, a small-scale experiment was conducted using a 30 L iron kiln to produce biochar from nine wood species and five straw species. Flue gas emissions from all feedstocks were visually observed and photographically documented. Comprehensive analyses were carried out on the resulting samples, including determination of uncarbonized materials, proximate analysis, and characterization of pH, electrical conductivity (EC), and water-holding capacity (WHC), which are relevant to the utilization of biochar in farmland. The results showed that all tested woody feedstocks achieved smokeless combustion in the iron kiln. In contrast, flue-cured tobacco stalk and rape straw frequently emitted smoke and even experienced flame extinction, resulting in failed biochar production. This confirmed that problematic feedstocks such as rape straw and flue-cured tobacco stalk compromise the smokeless advantage of flame curtain pyrolysis kilns. Notably, under conditions of low biochar production, the fixed carbon content of flue-cured tobacco stalk biochar exceeded 50%, and the biochar yield surpassed 10%. Therefore, elucidating the combustion inhibition mechanisms and eliminating these inhibiting factors would not only provide a theoretical foundation for processing straw biomass in flame curtain kilns, but also enable full realization of their smokeless potential in handling straw materials.



Keywords: biochar, flame curtain iron kiln, smokeless pyrolysis, woody feedstocks, straw feedstocks

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1. Introduction

In recent years, flame curtain pyrolysis kilns (also known as Kon-Tiki kilns) have been employed as a low-tech approach

for biochar production, representing a highly effective nature-based solution for climate change mitigation in the developing world, including China^[1]. Moreover, this technology is well-suited for agricultural-scale biochar preparation

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owing to its advantages of high yield, smokeless operation, and in-situ production capability^[2].

The efficiency of traditional charcoal production methods is approximately 10%–22% (calculated based on oven-dry wood with 0% moisture content). Just one ton of smouldering wood pollutes roughly 700000 m³ of air. Expressed in grams per kilogram of dry matter burned, emissions from a conventional charcoal production process are approximately 10 times higher than those from standard wood burning. The corresponding emission factor (21 g CH₄ kg⁻¹ dm) is 4–20 times greater than that observed in other types of combustion. Among these emissions, methane is 21 times more potent and damaging to the greenhouse effect than CO₂^[3]. For an intuitive comparison, Table 1 summarizes the emission factors of flame curtain kilns alongside those of traditional non-retort kilns and improved retort kilns reported in the literature. Flame curtain kilns emit statistically significantly lower amounts of CO, products of incomplete combustion (PIC), and NO_x than traditional kilns ($p < 0.05$), with CO emissions reduced by approximately 89% relative to conventional systems. Their higher CO₂ emissions indicate more complete combustion. Methane concentrations in flame curtain kilns remain predominantly below the detection limit of 0.1% (approximately 10 g kg⁻¹ biochar); however, occasional spikes reaching 1%–3% (100–300 g kg⁻¹ char) have been observed, coinciding with instances where the flame curtain was largely absent due to overfeeding. This underscores the pivotal role of the flame curtain in maintaining low emissions^[4].

Even modern pyrolysis units, such as the Pyreg 500, take this “low-tech” kiln as their benchmark for clean burning^[7]. Conversely, for medium-sized pyrolysis plants with an annual output of 700 tons of biochar, the moisture content of feedstock is strictly controlled between 8.6% and 20.9%^[7], as processing high-moisture materials is neither economically viable nor environmentally sound. However, self-heating carbonization flame curtain pyrolysis kilns have been successfully employed to treat feedstock with moisture content of 7%, 8%, 18%, 27%, and even as high as 48%^[8]. This eliminates the need for outdoor air-drying exceeding two months to achieve a moisture content of 15%–20% prior to process-

ing^[9]. Consequently, the smokeless advantages of flame curtain pyrolysis kilns have been somewhat mythologized. Specifically, clean burning is invariably attributed to the fundamental structure and operating principles of the flame curtain pyrolysis kiln^[10], while the contribution of feedstock properties remains overlooked.

Although flame curtain kilns have been applied to a wide range of feedstocks, existing literature has largely focused on kiln design and operating principles as the primary determinants of smokeless performance, while the role of feedstock properties has received comparatively little attention. Specifically, systematic comparisons between woody and straw-based feedstocks regarding their pyrolysis behavior, volatile release patterns, and combustion stability in flame curtain systems remain scarce.

From 2014 to the present, flame curtain pyrolysis kilns have been utilized to process a diverse range of feedstocks, including *Eupatorium adenophorum*^[4,8,9], wood and rice husks^[4], durian wood logs^[10], miscellaneous tree species (*Prosopis velutina*, *Fraxinus excelsior*, *Casuarina equisetifolia*, *Eucalyptus* spp., *Ficus benjamina*, *Schinus molle*, *Pinus cembroides*, *Bougainvillea* spp., Family Arecaceae)^[8], pruning wood^[11], oil palm fronds^[2], bamboo scraps^[12], vine wood^[13], hardwood chips^[14], pine tree^[15], animal bones^[16], as well as wood and plum stones^[13,17]. Although only a limited number of studies^[4] have quantified flue gas emissions using the carbon balance method, there is grounds to believe that these materials can achieve effective smokeless combustion in flame curtain pyrolysis kilns, given that the flue gas is readily assessable by direct visual observation.

However, according to our field experience from 2021 to 2023, attempts to pyrolyze rape straw in iron kilns exceeding 200 L resulted in frequent flameout and heavy smoke emissions over the course of a night; upgrading to a 2000 L iron kiln failed to ameliorate the situation. Consequently, in order to verify the hypothesis that the smokeless advantage of flame curtain pyrolysis depends not solely on kiln structure and operating principle but also on feedstock types, a small-scale iron kiln (30 L) was employed to produce biochar from nine wood species and five straw species. Combustion behavior was observed and photographically documented. Carbon

Table 1. Comparison of emission factors between flame curtain kilns, traditional non-retort kilns, and improved retort kilns (g kg⁻¹ biochar, mean ± SD, $n = 3$).

Pollutant	Flame curtain kiln ^[4]	Traditional non-retort kiln ^[5]	Improved retort kiln ^[5]	Remarks
CO ₂	4300 ± 1700	2380 ± 973	1950 ± 209	Flame curtain: most complete combustion
CO	54 ± 35	480 ± 141	157 ± 64	Flame curtain ↓ ~89% vs. traditional
CH ₄	30 ± 60 ¹	54 ± 29	24 ± 17	Highly moisture-dependent
Non-methane volatile organic compounds (NMVOC)	6 ± 3	13 ± 3.8	6.1 ± 3.4	Flame curtain comparable to retort
PM ₁₀ /total suspended particles (TSP)	11 ± 15 (PM ₁₀)	7.9 ± 2.6 (TSP)	12 ± 18 (TSP)	No significant difference
PIC ²	100 ± 83	554 ± 138	200 ± 97	Flame curtain ↓ ~82% vs. traditional
NO _x	0.4 ± 0.3	4.3 ± 1.6	1.8 ± 1.0	Flame curtain ↓ ~91% vs. traditional

¹ CH₄ emissions from flame curtain kilns are highly dependent on feedstock moisture content; with dry feedstock ($\leq 15\%$ moisture), CH₄ can drop below 5 g kg⁻¹ biochar^[6].

² PIC (products of incomplete combustion) = CO + NMVOC + CH₄ + PM₁₀/TSP (particulate matter).

stability of the resulting samples was assessed through determination of uncarbonized material content and proximate analysis. Additionally, pH, electrical conductivity (EC), and water-holding capacity (WHC)—properties pertinent to biochar application in soil amendment—were characterized.

2. Materials and methods

2.1. Raw materials

All feedstocks were sourced from the farms of Yunnan Vocational College of Agriculture, comprising nine wood species and five straw species, as detailed in Table 2. The raw materials were individually air-dried under ambient conditions and subsequently stored indoors. All feedstocks were conditioned to a moisture content below 15% (wet basis) prior to use. To ensure compatibility with the 30 L iron kiln (top diameter: 50 cm), all materials were cut or selected to a maximum dimension of < 50 cm. Woody branches and longer straws were shortened as needed, while irregular-shaped feedstocks such as pine cones and corn cobs retained their original morphology. This practical size constraint, together with the uniformly low moisture content, ensured consistent baseline conditions for comparing pyrolysis behavior across different feedstocks.

Table 2. Feedstock types and varieties.

Number	Feedstocks	Wood	Straw
1	Nectarine branch	√	—
2	Pear branch	√	—
3	Walnut twig	√	—
4	Chestnut tree branch	√	—
5	Persimmon branch	√	—
6	Pine cone	√	—
7	Palm branch	√	—
8	Thin bamboo	√	—
9	Grape vine	√	—
10	Rape straw	—	√
11	Flue-cured tobacco stalk	—	√
12	Rice straw	—	√
13	Corn stalk	—	√
14	Corn cob	—	√

2.2. Iron kiln and small-scale biochar preparation

Test specimens were processed using the smallest-dimension iron kiln illustrated in Fig. 1 (with dimensions detailed in Table 3), yielding a limited quantity of biochar for subsequent analysis.

A small quantity of feedstock was arranged to form miniature “wood chimneys” or “pyramid pyres” within the iron kiln, and then ignited by spraying anhydrous ethanol (99.8% ethanol content); only minimal additional feedstock was intro-



Fig. 1. Flame curtain iron kilns. The leftmost one is the smallest and was used for the small-scale tests.

duced during this ignition phase. Upon completion of combustion, the pyrolyzed material was discharged from the kiln onto a soil sieve to isolate it from air and allow natural cooling. Owing to the limited quantity produced, samples were collected using the quartering method. The samples were subsequently pulverized in a Chinese herbal medicine crusher for 50 s.

It should be noted that the flame curtain kiln is an open-system, self-heating pyrolysis device. Unlike industrial or laboratory-scale pyrolyzers (e.g., tube furnaces), the temperature profile in this system is not externally controlled but is governed by the combustion behavior of the feedstock itself. The process proceeds through spontaneous ignition, establishment of a self-sustaining flame curtain, and continued pyrolysis until the feedstock is consumed. Consequently, conventional parameters such as “heating rate” and “constant temperature duration” are neither defined nor applicable in this low-technology system. Instead, the process was monitored by visual observation of the flame curtain and smoke emissions, as described in Section 2.3.1.

2.3. Characterization methods

2.3.1. Photographic documentation

Following ignition, combustion behavior and smoke emissions were recorded using a mobile phone camera under relatively calm, windless conditions during stable combustion.

2.3.2. Determination of uncarbonized material

Uncarbonized matter was quantified in accordance with the standard method for “Test methods of wooden activated carbon—Determination of uncarbonized substances” (GB/T 12496.13-1999)^[18]. The absorbance of the resulting solution at 370 nm was measured using an M4 UV-Vis spectrophotometer (Shanghai Mapada Instruments Co., Ltd.).

2.3.3. Proximate analysis

Moisture content, crude ash, ash, volatile matter, and fixed carbon contents of both biochar and air-dried raw materials were determined and calculated following the “Proximate analysis of solid biofuels” (GB/T 28731-2012)^[19] and “Proximate analysis of coal” (GB/T 212-2008)^[20] standard methods.

Table 3. Dimensions of the flame curtain iron kiln used for the small-scale tests.

Kiln roof diameter (cm)	Bottom diameter (cm)	Depth (cm)	Capacity (L)	Angle* (°)	Thickness (cm)
50	20	30	30	61–63	0.5

Note: * is the angle between the cone and the horizontal plane.

2.3.4. pH, EC, and WHC measurements

Biochar was combined with deionized water at a mass-to-volume ratio of 1:20 (w/v) in a conical flask, which was then sealed with parafilm. The flask was equilibrated on a reciprocating shaker at 120 rpm for 90 min^[21]. Subsequently, following the “Standard test method for granular activated carbon from coal—Determination of water absorption” (GB/T 7702.5-1997)^[22], the equilibrated suspension was vacuum-filtered under 0.8 kPa pressure for approximately 5 min. The probes of a pH meter and conductivity meter were immersed in the filtrate, while the filter residue was promptly transferred from the filter paper to a pre-weighed small beaker using a spatula; stable pH and electrical conductivity (EC) values were then recorded. The filter residue was dried to constant weight in a forced-air drying oven at 40 °C and reweighed. Finally, the water-holding capacity (WHC) of the biochar was calculated.

3. Results and discussion

3.1. Rationale for using qualitative visual observation

In this study, combustion performance was assessed primarily by visual observation of smoke emissions and flame behavior. We acknowledge that this qualitative method does not provide quantitative emission data (e.g., gas concentrations, particulate matter), which is a limitation of the present work. However, the primary aim of this study was to conduct a qualitative screening of feedstocks based on the binary criterion of “smokeless” versus “smoky” combustion—a distinction that can be unambiguously judged by the presence or absence of visible smoke. This binary classification is sufficient for the initial identification of feedstocks that are compatible or incompatible with the smokeless operation of flame curtain kilns.

Quantitative measurements (e.g., carbon balance method or online gas analyzers) would be more meaningful after problematic feedstocks are successfully pretreated to achieve smokeless combustion, as the emission profiles of pretreated materials are of greater practical relevance for environmental assessment and process optimization. At this screening stage, however, instrumental quantification of emissions from inherently smoky feedstocks would provide limited insight, since their combustion is already unsustainable and their biochar yields are low.

Therefore, for this initial screening study, visual observation was considered sufficient and pragmatic. It allowed us to rapidly evaluate a relatively large number of feedstocks (14 types) under consistent conditions and to identify those warranting further investigation. Future studies will employ instrumental methods to quantify emissions from pretreated feedstocks and to establish quantitative relationships between feedstock properties and emission factors.

Similarly, regarding biochar yield data, we acknowledge the lack of parallel tests, which is consistent with our qualitative screening objective. Quantitative yield analysis will be conducted in future studies once problematic feedstocks can be successfully pretreated to achieve smokeless combustion. In the present study, the yield data serve only as a reference to

indicate the relative performance of different feedstocks under the same small-scale conditions, rather than as definitive production yields for industrial applications.

3.2. Effect of feedstock type on flue gas emissions

3.2.1. Influence of woody feedstocks on flue gas emission performance

Combustion photographs of the tested woody feedstocks are arranged sequentially in a 3 × 3 grid, as presented in Fig. 2. All nine wood species were capable of smokeless combustion at the base of the 30-liter iron kiln. Pine cone exhibited a distinct combustion behavior compared to the other woody feedstocks, characterized by alternating flames and smoke emissions. A plausible explanation for this phenomenon is the structural heterogeneity within the pine cone. The outer scales are flaky, providing a large surface area for oxygen contact and promoting vigorous combustion, whereas the central core is spherical and dense, presenting a limited oxygen contact area and rendering it susceptible to smoldering and flame extinction. The contrasting combustion characteristics between the outer and inner regions may give rise to the observed alternation between flaming and smoky conditions. Therefore, based on visual observation of the combustion process, it can be concluded that the smokeless advantage conferred by the operating principle of the flame curtain pyrolysis kiln remains unaffected by the nine woody feedstocks tested.



Fig. 2. Combustion photographs of nine wood species taken under calm, windless conditions (ambient temperature: 20–25 °C). (a) Nectarine branches, (b) Pear branches, (c) Walnut twigs, (d) Chestnut tree branches, (e) Persimmon branches, (f) Pine cone, (g) Palm branches, (h) Thin bamboo, (i) Grape vine.

3.2.2. Influence of straw feedstocks on flue gas emission performance

As observed with woody feedstocks, the three straw species

tested achieved smokeless combustion in the 30-liter iron kiln, as illustrated in Fig. 3. Rice straw, corn stalk, and corn cob exhibited no detrimental effects on the smokeless advantage. Notably, among all feedstocks evaluated, only corn cob retained its structural integrity throughout pyrolysis, yielding intact biochar rather than fragmenting into pieces.

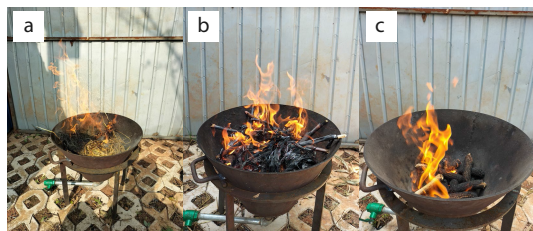


Fig. 3. Combustion photographs of three straw species taken under calm, windless conditions (ambient temperature: 20–25 °C). (a) Rice straw, (b) Corn stalk, (c) Corn cob.

However, the remaining two straw feedstocks exhibited adverse effects on smokeless combustion, as depicted in Fig. 4. Upon ignition of the “wood chimney” structure constructed from rape straw, the flame was immediately extinguished, accompanied by voluminous thick smoke emission, as soon as a small quantity of rape straw was introduced. Following flame reignition and subsequent rape straw addition, the cycle of “flame extinction-heavy smoke emission” recurred rapidly, manifesting a repetitive pattern of “combustion-feeding-smoking”.

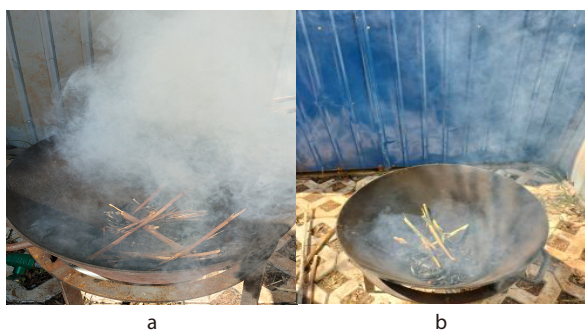


Fig. 4. Combustion photographs of two straw species taken under calm, windless conditions (ambient temperature: 20–25 °C). (a) Flue-cured tobacco stalk, (b) Rape straw.

The combustion performance of flue-cured tobacco stalk was the poorest. Once the “wood chimney” assembled from flue-cured tobacco stalk was ignited, it immediately entered a state of simultaneous burning and smoke emission, with both smoke concentration and emission rate escalating continuously. Within a short duration, the flame progressively diminished until complete extinction, necessitating re-ignition.

The shared pith structure present in both rape straw and flue-cured tobacco stalk may contribute to their inferior combustion behavior and propensity for smoke emission; however, the underlying mechanism remains elusive and warrants further investigation.

Nevertheless, one conclusion is unequivocal: based on visual observation of the combustion process, the smokeless

advantage conferred by the operating principle of the flame curtain pyrolysis kiln is, to a certain extent, negatively affected by these tested straw feedstocks.

3.3. Effect of feedstock type on uncarbonized material determination results

3.3.1. Influence of feedstock type on solution color in uncarbonized material determination

For visual comparison, one colorimetric tube containing the solution was taken from each of the three replicates and arranged sequentially, as presented in Fig. 5. Solutions a, b, c, e, f, and i exhibited a brownish-black hue, whereas solutions d, g, l, and m appeared brownish-tan. Solutions k and n were dark yellow, whereas h and j were golden yellow. The transparency of all feedstock solutions was markedly lower than that of the reference solution o. Given the pronounced color discrepancies between the test feedstock solutions and the reference solution, it can be confidently concluded that all feedstock samples failed the uncarbonized material analysis, which is entirely consistent with the actual absence of carbonization treatment. Notably, the solution colors of woody feedstocks were generally darker than those of straw-based feedstocks, attributable primarily to the typically higher lignin content in woody materials compared to straw-based ones. This color difference suggests that lignin-derived chromophores are more abundant in woody biomass. More importantly, the marked clarification of all biochar-derived solutions (Fig. 6) provides direct visual evidence that pyrolysis effectively decomposes these chromophoric organic compounds, thereby confirming successful carbonization.

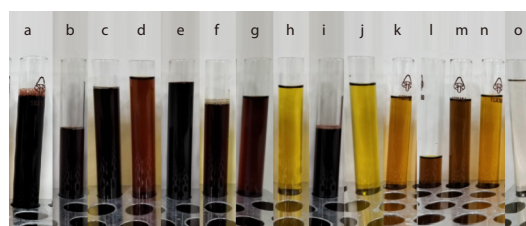


Fig. 5. Color comparison of solutions photographed against a white wall background. (a) Nectarine branch, (b) Pear branch, (c) Walnut twig, (d) Chestnut tree branch, (e) Persimmon branch, (f) Pine cone, (g) Palm branch, (h) Thin bamboo, (i) Grape vine, (j) Rape straw, (k) Flue-cured tobacco stalk, (l) Rice straw, (m) Corn stalk, (n) Corn cob, and (o) Reference.

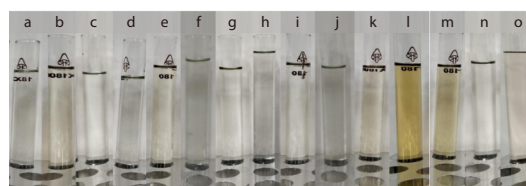


Fig. 6. Color comparison of biochar-derived solutions photographed against a white wall background. (a) Nectarine branch, (b) Pear branch, (c) Walnut twig, (d) Chestnut tree branch, (e) Persimmon branch, (f) Pine cone, (g) Palm branch, (h) Thin bamboo, (i) Grape vine, (j) Rape straw, (k) Flue-cured tobacco stalk, (l) Rice straw, (m) Corn stalk, (n) Corn cob, and (o) Reference.

Unlike the raw materials, the solutions of the tested biochar became transparent, with only solutions l and m exhibiting slight color intensification, as illustrated in Fig. 6. Given that the color discrepancies between the tested biochar solutions and the reference solution were not pronounced, a definitive assessment of the uncarbonized material analysis results could not be made based solely on solution color.

3.3.2. Influence of feedstock type on light absorption coefficient of solutions

The criterion for determining uncarbonized material follows the Chinese national standard GB/T 12496.13-1999. A reference solution was prepared according to the standard, and its light absorption coefficient at 370 nm was measured as the benchmark. A biochar sample was considered qualified (i.e., sufficiently carbonized) if its light absorption coefficient was below the corresponding reference value of its measurement batch (see notes to Table 4), and unqualified if it was equal to or above that value. The same benchmark (0.119/0.121) was applied consistently to all biochar samples, regardless of feedstock type. The measured light absorption coefficients for solutions prepared from the various test feedstocks and biochars are presented in Table 4.

With the exception of rice straw (3.936) and corn stalk (3.995), the absorption coefficients of all tested raw material solutions reached the upper limit of 4.000. The absorption coefficients of biochar solutions derived from carbonized feedstocks decreased by one to two orders of magnitude compared to their corresponding raw materials, confirming effective carbonization. However, qualitative analysis revealed non-compliance for three woody materials: pear branches (0.140), walnut twigs (0.391), and persimmon branches (0.166), as well as three straw-based materials: flue-cured tobacco stalk (0.141), rice straw (0.799), and corn stalk (0.326). All six samples exceeded the 0.119 threshold for uncarbonized residues established by GB/T 12496.13-1999^[18]. The non-compliance observed for uncarbonized residues in certain biochar samples is attributable to the extremely limited

feedstock quantity, which precluded the establishment of a thermally stable environment within the iron kiln conducive to optimal pyrolysis.

Notably, the biochar derived from rape straw—which exhibited frequent smoke emissions during combustion—passed the uncarbonized residue analysis. This outcome may be attributable to the fact that GB/T 12496.13-1999^[18] is primarily calibrated for lignin-rich woody biomass rather than straw materials with comparatively lower lignin content.

3.4. Effect of feedstock type on proximate analysis results

3.4.1. Influence of feedstock type on biomass proximate analysis

On a dry basis, the crude ash (at 550 °C), ash (at 815 °C), volatile matter (at 920 °C), and fixed carbon contents of the raw materials are presented in Table 5. All tested feedstocks exhibited typical biomass characteristics of high volatile matter content and low fixed carbon yield, consistent with the fundamental thermochemical properties of lignocellulosic materials. Among them, rice straw exhibited the lowest volatile matter content, while corn cobs demonstrated the highest, reflecting inherent compositional differences among straw-based feedstocks.

3.4.2. Influence of feedstock type on biochar proximate analysis

Table 6 presents the dry-basis compositional analysis of the biochars, including crude ash content (550 °C), residual ash content (815 °C), volatile matter yield (920 °C), and fixed carbon proportion.

Wood-derived biochar exhibited lower crude ash content than straw-derived biochar, consistent with general patterns. However, the crude ash level in wood biochar remained relatively high, which was attributed to the minimal feedstock quantity used in pyrolysis. The excessively high crude ash content in straw-derived biochar likely constitutes a secondary cause of smoke emission during combustion of rape straw and flue-cured tobacco stalk. The excessively high

Table 4. Absorbance of raw material, biochar, and reference solution at 370 nm (mean $\pm$ SD, $n = 3$).

Number	Material name	Raw material	Biochar	Reference
1	Nectarine branch	4.000 $\pm$ 0.000	0.044 $\pm$ 0.005	0.119 $\pm$ 0.000
2	Pear branch	4.000 $\pm$ 0.000	0.140 $\pm$ 0.008	0.119 $\pm$ 0.000
3	Walnut twig	4.000 $\pm$ 0.000	0.391 $\pm$ 0.107	0.119 $\pm$ 0.000
4	Chestnut branch	4.000 $\pm$ 0.000	0.040 $\pm$ 0.003	0.119 $\pm$ 0.000
5	Persimmon branch	4.000 $\pm$ 0.000	0.166 $\pm$ 0.004	0.119 $\pm$ 0.000
6	Pine cone	4.000 $\pm$ 0.000	0.067 $\pm$ 0.009	0.121 $\pm$ 0.000
7	Palm branches	4.000 $\pm$ 0.000	0.051 $\pm$ 0.003	0.119 $\pm$ 0.000
8	Thin bamboo	4.000 $\pm$ 0.000	0.085 $\pm$ 0.005	0.119 $\pm$ 0.000
9	Grape vine	4.000 $\pm$ 0.000	0.079 $\pm$ 0.004	0.119 $\pm$ 0.000
10	Rape straw	4.000 $\pm$ 0.000	0.052 $\pm$ 0.001	0.119 $\pm$ 0.000
11	Flue-cured tobacco stalk	4.000 $\pm$ 0.000	0.141 $\pm$ 0.005	0.119 $\pm$ 0.000
12	Rice straw	3.936 $\pm$ 0.015	0.799 $\pm$ 0.067	0.119 $\pm$ 0.000
13	Corn stalk	3.995 $\pm$ 0.008	0.326 $\pm$ 0.072	0.119 $\pm$ 0.000
14	Corn cob	4.000 $\pm$ 0.000	0.111 $\pm$ 0.007	0.119 $\pm$ 0.000

Note: The reference absorbance was 0.119 for the first batch of samples and 0.121 for the second batch, as the reference solution was re-prepared due to insufficient volume. The batch-specific reference values were used for qualification assessment.

Table 5. Proximate analysis results of raw materials (mean $\pm$ SD, $n = 3$).

Number	Raw material	Crude ash (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)
1	Nectarine branch	2.05 $\pm$ 0.14	0.49 $\pm$ 0.11	70.33 $\pm$ 0.13	17.41 $\pm$ 0.26
2	Pear branch	1.92 $\pm$ 0.10	0.23 $\pm$ 0.06	69.77 $\pm$ 0.71	19.22 $\pm$ 0.43
3	Walnut twig	4.29 $\pm$ 0.68	1.48 $\pm$ 0.35	69.57 $\pm$ 0.51	15.32 $\pm$ 0.39
4	Chestnut tree branch	2.08 $\pm$ 0.17	0.29 $\pm$ 0.06	73.06 $\pm$ 0.09	18.10 $\pm$ 0.24
5	Persimmon branch	1.74 $\pm$ 0.06	0.12 $\pm$ 0.04	68.43 $\pm$ 0.83	16.67 $\pm$ 0.55
6	Pine cone	1.14 $\pm$ 0.15	0.29 $\pm$ 0.04	67.90 $\pm$ 0.22	16.94 $\pm$ 0.30
7	Palm branch	3.36 $\pm$ 0.06	0.54 $\pm$ 0.04	70.99 $\pm$ 0.07	19.35 $\pm$ 0.13
8	Thin bamboo	0.97 $\pm$ 0.05	0.20 $\pm$ 0.05	72.05 $\pm$ 0.19	16.05 $\pm$ 0.19
9	Grape vine	2.48 $\pm$ 0.04	0.40 $\pm$ 0.03	71.44 $\pm$ 0.23	20.52 $\pm$ 0.26
10	Rape straw	5.11 $\pm$ 0.17	2.09 $\pm$ 0.12	70.74 $\pm$ 0.21	18.02 $\pm$ 0.35
11	Flue-cured tobacco stalk	4.42 $\pm$ 0.12	1.39 $\pm$ 0.07	67.19 $\pm$ 0.42	18.41 $\pm$ 0.31
12	Rice straw	9.17 $\pm$ 0.13	0.91 $\pm$ 0.03	56.45 $\pm$ 15.92	25.44 $\pm$ 0.20
13	Corn stalk	4.35 $\pm$ 0.11	0.58 $\pm$ 0.04	68.09 $\pm$ 0.49	17.33 $\pm$ 0.30
14	Corn cob	0.94 $\pm$ 0.12	0.15 $\pm$ 0.06	74.65 $\pm$ 0.52	16.78 $\pm$ 0.39

Table 6. Proximate analysis results of biochars.

Number	Biochar	Crude ash (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)
1	Nectarine branch	11.92 $\pm$ 0.10	2.89 $\pm$ 0.07	11.42 $\pm$ 1.03	75.98 $\pm$ 0.75
2	Pear branch	11.87 $\pm$ 0.16	3.01 $\pm$ 0.12	12.94 $\pm$ 0.21	74.42 $\pm$ 0.36
3	Walnut twig	21.43 $\pm$ 0.06	6.56 $\pm$ 0.08	17.65 $\pm$ 0.80	59.93 $\pm$ 0.71
4	Chestnut tree branch	7.46 $\pm$ 0.11	1.57 $\pm$ 0.17	9.41 $\pm$ 0.17	82.60 $\pm$ 0.27
5	Persimmon branch	9.13 $\pm$ 0.28	2.36 $\pm$ 0.11	14.22 $\pm$ 0.09	73.41 $\pm$ 0.34
6	Pine cone	4.39 $\pm$ 0.05	0.33 $\pm$ 0.09	15.60 $\pm$ 0.14	79.92 $\pm$ 0.17
7	Palm branch	18.90 $\pm$ 0.26	3.82 $\pm$ 0.09	8.62 $\pm$ 1.51	71.85 $\pm$ 0.80
8	Thin bamboo	8.07 $\pm$ 2.20	1.33 $\pm$ 0.11	12.13 $\pm$ 0.39	79.34 $\pm$ 2.29
9	Grape vine	10.57 $\pm$ 0.07	2.30 $\pm$ 0.12	11.63 $\pm$ 1.42	75.79 $\pm$ 1.41
10	Rape straw	65.46 $\pm$ 2.51	16.97 $\pm$ 4.72	17.88 $\pm$ 1.37	14.53 $\pm$ 2.82
11	Flue-cured tobacco stalk	22.99 $\pm$ 0.11	8.28 $\pm$ 2.78	13.45 $\pm$ 0.11	59.68 $\pm$ 0.18
12	Rice straw	49.07 $\pm$ 0.04	4.64 $\pm$ 0.19	11.25 $\pm$ 3.13	38.52 $\pm$ 3.48
13	Corn stalk	20.62 $\pm$ 0.06	5.38 $\pm$ 1.27	14.04 $\pm$ 0.13	62.69 $\pm$ 0.21
14	Corn cob	5.14 $\pm$ 0.09	1.52 $\pm$ 0.10	8.79 $\pm$ 0.41	84.73 $\pm$ 0.29

crude ash content in straw-derived biochar may contribute to smoke emission during combustion of rape straw and flue-cured tobacco stalk. One possible mechanism is that elevated ash levels could form an inorganic barrier layer that inhibits volatile release, thereby exhibiting a flame-retardant effect. More importantly, other factors such as the K/Cl ratio—known to affect tobacco combustibility—may play an even more critical role. Nevertheless, the exact mechanism remains unclear. Future studies involving detailed ash composition analysis (e.g., by XRF) and microstructural characterization (e.g., by SEM-EDS) are required to elucidate the melting and coating behavior of mineral components and their contribution to flame retardancy. The fixed carbon content of rape straw biochar was the lowest among all tested materials. Even when combustion occurs without smoke emission in flame-curtain kilns, its markedly low fixed carbon content (< 50%) renders the conversion of rape straw to biochar economically and environmentally unviable. The fixed carbon content of flue-cured tobacco stalk biochar was comparable to that of walnut twig biochar. If the issue of smoke emission can be resolved and the underlying mechanism for smoke suppression elucidated, this would hold both scientific and practical significance. Corn cob biochar exhibited the smallest differ-

ence between crude ash and total ash contents, indicating the lowest inorganic carbon content. Meanwhile, it demonstrated the highest fixed carbon content, suggesting that corn cob biochar possesses the greatest carbon sequestration potential.

3.5. Effect of feedstock type on pH, EC, and WHC results

The analytical results for pH, EC, and WHC are presented in Table 7. The pH values indicate that all biochars exhibit alkaline properties, suggesting their potential for regulating acidic soils and ameliorating soil pH conditions. Among straw-derived biochars, only corn cob showed an electrical conductivity (EC) below 1.8 mS cm⁻¹. For wood-derived biochars, walnut twig, persimmon branch, pine cone, palm branch, and thin bamboo all demonstrated EC values < 1.8 mS cm⁻¹, with pine cone exhibiting an EC one order of magnitude lower than the 1.8 mS cm⁻¹ threshold. These findings confirm that these biochars pose no risk of salt stress to crop^[23]. Moreover, it is anticipated that under large-scale production conditions, the EC values of wood-derived biochars will decrease significantly, whereas straw-derived biochars—owing to their inherently higher crude ash content—will experience relatively lim-

Table 7. pH, EC, and WHC results of biochars.

Number	Biochar	pH	EC ($\mu\text{s cm}^{-1}$)	WHC (%)
1	Nectarine branch	10.10 $\pm$ 0.03	4846.00 $\pm$ 41.63	172.78 $\pm$ 29.12
2	Pear branch	9.83 $\pm$ 0.07	2186.00 $\pm$ 51.32	104.73 $\pm$ 6.63
3	Walnut twig	9.65 $\pm$ 0.03	1130.00 $\pm$ 22.01	115.89 $\pm$ 5.82
4	Chestnut tree branch	10.71 $\pm$ 0.02	5946.00 $\pm$ 70.95	122.15 $\pm$ 8.43
5	Persimmon branch	9.29 $\pm$ 0.02	1000.00 $\pm$ 2.08	145.86 $\pm$ 9.51
6	Pine cone	8.05 $\pm$ 0.04	285.00 $\pm$ 14.98	69.71 $\pm$ 6.92
7	Palm branch	9.63 $\pm$ 0.03	1500.00 $\pm$ 15.37	112.60 $\pm$ 1.87
8	Thin bamboo	9.31 $\pm$ 0.03	1700.00 $\pm$ 27.39	100.60 $\pm$ 8.29
9	Grape vine	9.86 $\pm$ 0.03	2160.00 $\pm$ 95.39	134.39 $\pm$ 7.42
10	Rape straw	11.4 $\pm$ 0.06	22533.00 $\pm$ 378.59	152.69 $\pm$ 7.15
11	Flue-cured tobacco stalk	9.94 $\pm$ 0.59	9806.00 $\pm$ 68.07	133.34 $\pm$ 7.41
12	Rice straw	10.43 $\pm$ 0.11	4976.00 $\pm$ 607.97	122.13 $\pm$ 32.95
13	Corn stalk	10.34 $\pm$ 0.08	6193.00 $\pm$ 140.12	151.51 $\pm$ 16.38
14	Corn cob	9.71 $\pm$ 0.01	1610.00 $\pm$ 6.11	97.60 $\pm$ 3.94

ited improvement. Except for pine cone biochar, the average water-holding capacity (WHC) of tested biochars was markedly higher than that of agricultural soils. The superior water retention performance of these biochars facilitates their field application for enhancing soil available water capacity, while simultaneously enabling their utilization as construction materials to improve humidity buffering and regulation capacity[24].

In this study, the high EC values of certain straw-derived biochars (e.g., rape straw: 22533 $\mu\text{s cm}^{-1}$; flue-cured tobacco stalk: 9806 $\mu\text{s cm}^{-1}$) indicate incomplete volatilization of alkali salts under the relatively low and uncontrolled temperatures of the flame curtain kiln. Notably, WHC values for these problematic feedstocks were already high (133%–152%), suggesting that WHC enhancement is not a priority for them.

Based on these findings, we propose differentiated optimization strategies for different feedstock types:

(1) To reduce EC (primary goal for problematic straw feedstocks such as rape straw and flue-cured tobacco stalk), which are inherently difficult to ignite, pre-treatment is necessary before pyrolysis. Effective pre-treatment options include water washing to remove soluble salts, co-pyrolysis with woody

biomass, or pelletization to improve combustion stability.

(2) To enhance WHC for biochars with relatively low values (e.g., pine cone biochar: 69.71%), maintaining a stable flame curtain through optimal feedstock moisture content ($\leq 15\%$) and controlled feeding rate is recommended to achieve moderate pyrolysis temperatures that preserve porous structures. For feedstocks that already yield high WHC biochars (e.g., rape straw and flue-cured tobacco stalk), WHC enhancement is not a priority; instead, reducing EC should be the primary focus.

These differentiated optimization strategies provide practical guidance for producing biochars with balanced EC and WHC for agricultural use.

3.6. Effect of feedstock type on biochar yield

Owing to the minimal feedstock quantities employed, the biochar yield data obtained in this study do not represent actual production conditions in flame curtain pyrolysis kilns; rather, they reflect yield performance when processing small-scale feedstock quantities in flame curtain iron kilns, as detailed in Table 8. Among all tested materials, nectarine branch biochar exhibited the highest production yield. Mean-

Table 8. Biochar yield measurement results.

Number	Biochar	Raw materials (kg)	Biochar (kg)	Biochar yield (%)
1	Nectarine branch	1.71	0.31	18.13
2	Pear branch	2.62	0.16	6.11
3	Walnut twig	1.62	0.14	8.64
4	Chestnut tree branch	2.64	0.23	8.71
5	Persimmon branch	2.76	0.25	9.06
6	pine cone	0.58	0.09	15.52
7	Palm branch	2.57	0.34	13.23
8	Thin bamboo	1.73	0.21	12.14
9	Grape vine	8.9	1.23	13.82
10	Rape straw	0.48	0.03	6.25
11	Flue-cured tobacco stalk	1.29	0.15	11.63
12	Rice straw	0.58	0.14	24.14
13	Corn stalk	3.76	0.45	11.97
14	Corn cob	1.58	0.17	10.75

Note: The raw materials are on an air-dry weight basis, and the moisture content is below 15%.

while, unlike rape straw, flue-cured tobacco stalk biochar also exceeded 10% (w/w) yield, demonstrating practical application potential.

3.7. Practical implications and scale-up considerations

It should be noted that in flame curtain pyrolysis, larger kiln scales generally facilitate more stable temperature fields and more complete combustion due to reduced relative heat losses and easier flame curtain maintenance. Based on our operational experience, the 30 L kiln used in this study is the minimum practical size for effective waste reduction. Because small-scale kilns represent the “worst-case” scenario (less stable temperature field, more prone to heat loss), feedstocks that achieve smokeless combustion in this 30 L kiln will perform even better in larger kilns, while problematic feedstocks (e.g., rape straw, flue-cured tobacco stalk) that already show smoke and flame instability at this scale will not be fundamentally improved by scale-up alone, as their inherent properties are the primary limiting factor. Therefore, the conclusions of this study are directly applicable to feedstock screening and pre-treatment development, rather than to direct industrial scale-up without addressing feedstock limitations. For practical applications, we recommend that operators first conduct a small-scale screening test using the 30 L kiln to identify whether a given feedstock is inherently compatible with flame curtain pyrolysis. If smokeless combustion is achieved at this scale, the feedstock can be confidently processed in larger kilns. If smoke and flame instability persist, pre-treatment (e.g., water washing, co-pyrolysis with woody biomass, or pelletization) should be prioritized before scaling up, as kiln scale alone cannot overcome intrinsic feedstock constraints. This tiered approach—small-scale screening followed by targeted pre-treatment and subsequent scale-up—provides a pragmatic pathway for expanding the range of feedstocks suitable for smokeless flame curtain pyrolysis, while avoiding the inefficiency of trial-and-error at industrial scale.

4. Conclusions

This study systematically evaluated the impact of feedstock type on smokeless pyrolysis performance in flame curtain iron kilns. A total of 14 feedstocks (nine wood species and five straw species) were assessed through combustion observation, uncarbonized material analysis, proximate analysis, and characterization of pH, EC, and WHC. The results revealed distinct differences in combustion stability and biochar quality across material types, further challenging the assumption that smokeless advantages are solely determined by kiln design. The following conclusions can be drawn:

All tested woody materials achieved stable, continuous smokeless combustion, confirming their compatibility with flame curtain kiln principles. In contrast, rape straw and flue-cured tobacco stalk exhibited frequent smoking, flame extinction, and self-extinguishing behavior due to inherent material properties (e.g., high ash content, low lignin levels, and poor cohesion).

Corn cob biochar demonstrated superior carbon stability (fixed carbon: 84.73%) and structural integrity, whereas rape

straw biochar showed the lowest fixed carbon content (14.53%) and highest ash accumulation, rendering it economically unviable despite its 6.25% biochar yield.

All biochars exhibited alkaline pH (8.05–11.40). Walnut twig, persimmon branch, pine cone, palm branch, thin bamboo, and corn cob biochars all showed EC values below 1.8 mS cm⁻¹, indicating suitability for soil amendment without salt stress risks. The high WHC (69.71%–172.78%) of most biochars further supports their utility in enhancing soil water retention, particularly under dryland farming conditions.

This study was conducted using a 30 L laboratory-scale kiln, which represents the minimum practical size for effective waste reduction and a “worst-case” scenario for combustion stability. Therefore, feedstocks that pass the smokeless test at this scale are expected to perform even better in larger kilns, and the conclusions are directly applicable to feedstock screening and pre-treatment development.

For problematic straw feedstocks that are difficult to ignite and sustain combustion (e.g., rape straw and flue-cured tobacco stalk), we recommend the following pre-treatment strategies: (1) water washing to remove soluble salts and ash-forming minerals; (2) co-pyrolysis with woody biomass to improve energy density; and (3) pelletization to enhance particle cohesion and packing density. These strategies are expected to improve combustion stability and enable smokeless pyrolysis in flame curtain kilns.

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Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

Chengjun Liao: Writing – original draft, Investigation, Methodology, Formal analysis, Conceptualization. **Liqun Tang:** Writing – review & editing, Methodology, Conceptualization. **Wanyue Zhao:** Writing – review & editing. **Changrong Ge:** Writing – review & editing, Methodology. **Yuying Shen:** Writing – review & editing. **Xiaoting Li:** Writing – review & editing.

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Use of AI statement

During the preparation of this work, the authors used Kimi in order to polish the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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