Original Research Open Access

Influence of cigar-type slow pyrolysis conditions on the physiochemical properties and conversion efficiency of biochar

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Received: 4 January 2026
Revised: 5 February 2026
Accepted: 27 February 2026
Published online: 13 March 2026

Abstract

Biochar quality is related to raw material, reactor type, and slow pyrolysis conditions. The slow pyrolysis of biomass with internal heating is widely used for the polygeneration of biochar and syngas because of its positive project value and market prospects. However, research on the characteristics of biochar generated via this approach is lacking. Here, we developed a novel cigar-type slow pyrolysis reactor with internal heating and reed straw pellet feedstock, and investigated the influence of draft direction, pyrolysis temperature, air distribution rate, and cooling type on the fixed carbon content, atomic ratios, specific surface area (SSA), cation exchange capacity (CEC), and polycyclic aromatic hydrocarbon (PAH) concentrations of biochar. The fixed carbon content of biochar fluctuated from 38.46% to 44.02% under different pyrolysis conditions; this fluctuation range was lower than that under slow pyrolysis with external heating. The H/C (hydrogen-to-carbon) and O/C (oxygen-to-carbon) ratios of biochar fluctuated within the ranges of 0.61–0.33 and 0.15–0.03, respectively, with variations in pyrolysis conditions, and did not exhibit a continuous decreasing trend as pyrolysis temperature rose. Pyrolysis conditions strongly influenced the SSA; at a pyrolysis temperature of 650 °C, the SSA of biochar derived under downdraft, low air distribution rate, and air insulation conditions was 1.46, 2.26, and 3.00 times that derived under updraft, high air distribution rate, and water cooling conditions, respectively. The biochar toxic equivalence quantity under all conditions was 0.39–5.68 μg/kg, far below the international threshold (3 mg/kg). The PAH concentration of biochar was substantially higher at a high air distribution rate than at a low air distribution rate and substantially higher with water cooling than with air insulation. These findings can be used to optimize industrial slow pyrolysis equipment and the large-scale production of biochar for agricultural applications.

Keywords: Draft direction, Controlled conditions, Physiochemical properties, Biochar, Cigar-type pyrolyzer

Highlights

- We developed an internally heated cigar-type pyrolyzer to explore biochar properties under varied pyrolysis conditions.
- Biochar was characterized according to conventional, functional, and cleanliness indices and conversion efficiency.
- The PAH concentration of biochar derived from cigar-type slow pyrolyzer was far below international thresholds.
- Our results can be used to optimize the large-scale slow pyrolysis of biochar for agricultural applications.

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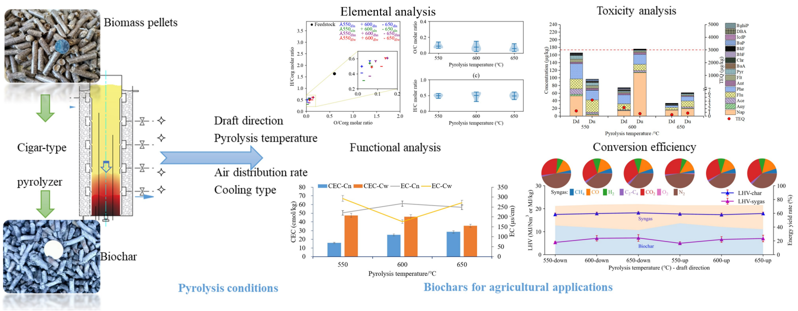
https://doi.org/10.48130/bchax-0026-0011

Graphical abstract



Introduction

Slow biomass pyrolysis is a thermochemical reaction performed under a moderate temperature (400–600 °C) and proper heating rate (< 10 °C/min) in an oxygen-depleted environment[1]. It is a promising technology for high-value biomass utilization[2]. Biochar is a carbon-rich material with high chemical stability derived from biomass using slow pyrolysis[3]. Crop straw, wood chips, rice husks, and other agroforestry residues are common feedstock materials produced abundantly annually in China[4]. Biochar stabilizes carbon in a form that is highly resistant to biodegradation and mineralization, a state that can be maintained for hundreds of years[5]; thus, biochar helps reduce CO_2 emissions by acting as a soil carbon sink[6]. Furthermore, biochar shows broad application prospects as a fertilizer and soil conditioner in agriculture[7] owing to its carbon-rich property, porous structure, and valuable nutrients[8].

Potential pollutants may form during biochar preparation, mainly polycyclic aromatic hydrocarbons (PAHs) and heavy metals[9]. PAHs, as a group of persistent organic contaminants, are predominantly associated with the slow pyrolysis of biomass[10]. PAHs are characterized by high toxicity, lipophilicity, and persistence, posing a risk to soil and water and representing teratogenic and carcinogenic hazards to the human body[11]. Therefore, cleanliness is also a key factor in biochar applications.

The conventional, functional, and cleanliness indices depend on several factors, and these were investigated by relevant scholars[12,13]. For example, biochars produced from five typical halophytes were characterized according to their porous structure to determine their agricultural value[14]. The impacts of pyrolysis conditions on the total nutrient and harmful element concentrations in biochar were revealed, and its total value as a fertilizer was determined[7]. Moreover, five typical solid wastes were pyrolyzed at different temperatures to assess the PAH content and toxicity of the resulting biochar[15]. Other studies have analyzed biochar's properties and agricultural applications[16]. However, all these studies employed batch slow pyrolysis with external heating, which differs markedly from continuous slow biomass pyrolysis with internal heating.

Although biochar has good potential to improve soil, its application feasibility is limited by its high production costs[17]. Compared to fixed-bed processing, a moving-bed reactor has many advantages, such as continuous production, product quality control, and convenient operation[17]; therefore, it represents a key area of technology development. Additionally, internal heating offers superior heat transfer efficiency due to its direct mode of energy delivery. Slow pyrolysis with internal heating has certain advantages regarding conversion efficiency and associated costs[18,19].

Therefore, we addressed the characteristics of biochar produced with an internally heated moving-bed pyrolysis reactor by developing a novel cigar-type pyrolyzer. The main purpose was to systematically study the impact of draft direction, pyrolysis temperature, air distribution rate, and cooling type on biochar's conventional, functional, and cleanliness indices and the approximate conversion efficiency. Finally, we determined the agricultural value of biochar derived from our novel pyrolyzer, which is beneficial for optimizing industrial slow pyrolysis equipment and the large-scale application of biochar to agriculture.

Materials and methods

Materials

The feedstock biomass pellets were produced from reed straw, and more than five million tonnes of reed straw are annually produced in China, with Heilongjiang, Liaoning, Inner Mongolia, Xinjiang, and Qinghai being the main production areas. If reed straw cannot be harvested and cleaned in time, it can lead to eutrophication and other pollutant emissions. The characteristics of the materials are listed in Table 1. The lower heating values and ultimate analysis of the materials and biochars were measured according to GB T 213 2008 and ASTM D4239, respectively.

Experimental equipment

A schematic of the biomass slow pyrolysis experimental system with an internally heated cigar-type pyrolyzer is shown in Fig. 1, which was independently developed by our research team. The pyrolyzer was a

Table 1 Characteristics of raw material biomass pellets produced from reed straw

Index	Parameter
Nominal diameter (mm)	8
Bulk density (kg/m^3)	580
Natural length (mm)	20–45
LHV (lower heating value) (MJ/kg)	15.65
Proximate analysis based on received basis (wt.%)	
Volatile content concentration	62.47
Fixed carbon concentration	11.14
Ash concentration	20.64
Moisture concentration	5.75
Ultimate analysis based on dry and ash-free basis (wt.%)	
Concentration of C element	51.34
Concentration of H element	7.01
Concentration of O element	40.89
Concentration of N element	0.77

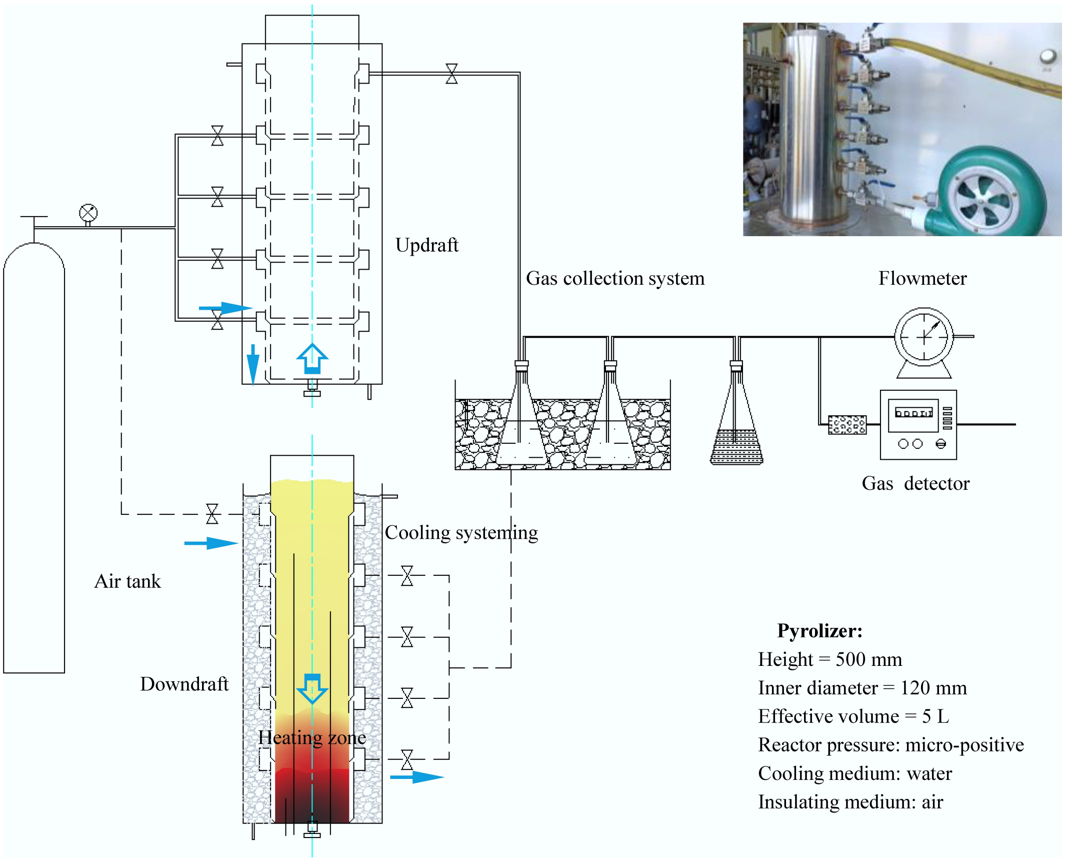


Fig. 1 Schematic diagram of the developed internally heated cigar-type pyrolyzer and photograph of the pyrolysis experimental system.

quasi-moving-bed reactor, and the heat required for pyrolysis originates from the combustion of some of the material. The pyrolysis temperature and heating rate can be adjusted by changing the air distribution, and the residence time of the biochar can be adjusted by changing the interlayer media of the cigar-type pyrolyzer. By switching the air inlet valves, the combustion and pyrolysis areas move up layer by layer, like a cigarette and a controllable moving-bed reactor. Updraft and downdraft conditions can be achieved by exchanging air inlets and syngas outlets. High-temperature syngas flows into a purification system comprising multi-stage condensation, a gas washer, and a moisture trap, and its flow rate and components are monitored in real time.

Analytical methods

The pyrolysis behaviour of biomass pellets was investigated according to different pyrolysis conditions. Pyrolysis temperatures of 550, 600, and 650 °C were selected based on pre-experiments and the desire to balance product quality and production efficiency. Under downdraft conditions, the heating rate was divided into two levels, controlled at a high air distribution rate (24 L/min) or a low air distribution rate (15 L/min). The residence time of the biochars was controlled by changing the interlayer media, which used either air as a thermal insulation medium or water as a cooling medium.

The specific surface area (SSA) was measured using a specific surface analyzer (Micromeritics ASAP 2460, USA) according to the Brunauer-Emmett-Teller (BET) standard. The pH value was measured using a conductivity meter (SANXIN SX650, China) according to the China National Standard (GB/T 7702.16). The concentration of PAHs of the biochars using a GC/MS (Agilent 6890-5975, USA) according to the China Industry Standard (HJ 805-2016).

The toxic equivalence quantity (TEQ) of PAHs[20,21] was expressed as follows[9]:

$$TEQ_{BaP} = \sum_{i=1}^{n} PAH_i \times TEF_{PAH_i} \quad (1)$$

where, TEQ_{BaP} is the toxic equivalence quantity using BaP as the baseline, PAH_i is the concentration of a specific PAH in the pellet char, and TEF_{PAHi} is the corresponding toxicity equivalency factor.

The energy conversion efficiency (η), representing the energy recovery rate, was expressed as follows[12]:

$$\eta = \frac{Q_{\text{biocharc}} + Q_{\text{syngas}} + Q_{\text{bio-oil}}}{Q_{\text{feedstock}}} \quad (2)$$

where, $Q_{biochar}$, Q_{syngas}, $Q_{bio\text{-}oil}$, and $Q_{feedstock}$ are the total latent heats of the biochar, syngas, bio-oil, and feedstock, respectively. This study ignored bio-oil's influence due to its relatively low yield rate.

Results and discussion

Conventional properties of biochar

Fixed carbon and ash

The proximate analysis results of biochars on the as-received basis are shown in Fig. 2. The concentration of ash increased continuously as pyrolysis temperature rose from 550 via 600 to 650 °C under the three control conditions owing to the increasing degree of devolatilization[12] and increasing gasification of the fixed carbon[22]. The highest ash concentration of the biochars reached 48.1%, which was also impacted by the feedstock (Table 1). For biochar application as a fertilizer, the ash

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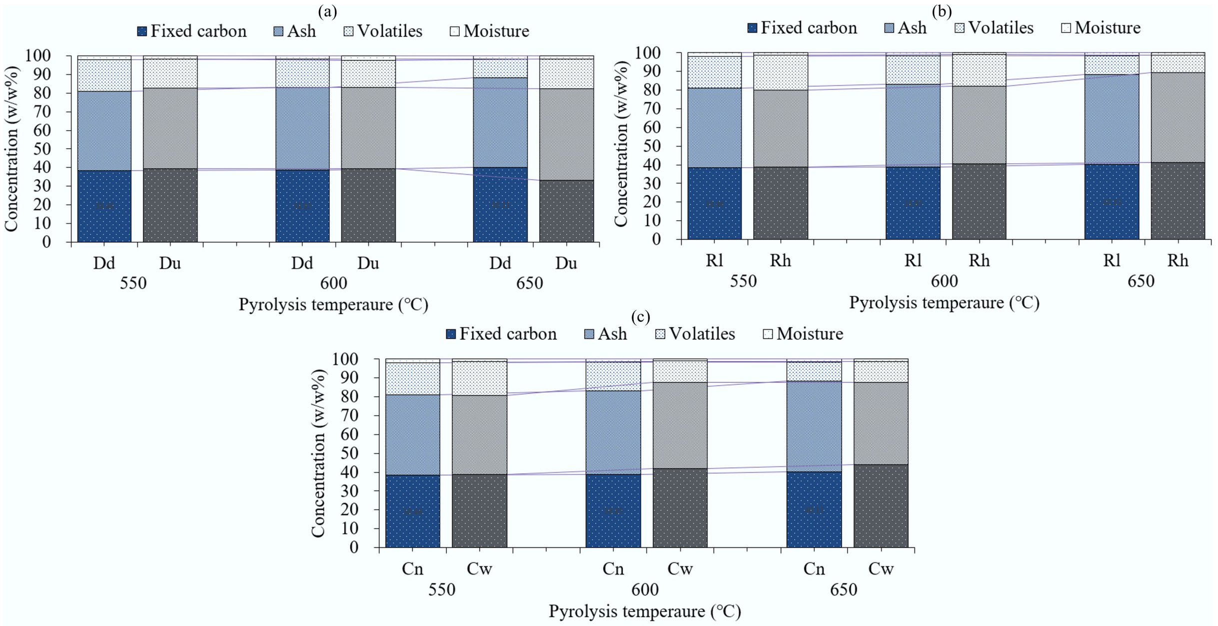

Fig. 2 Influence of (**a**) draft direction, (**b**) air distribution rate, and (**c**) cooling type on the fixed carbon and ash contents of biochar. Dd: downdraft condition, Du: updraft condition, Rl: low air distribution rate, Rh: high air distribution rate, Cn: air insulation, Cw: water cooling.

concentration is used as a performance index owing to the presence of P, K, and trace elements for crop growth in some ash. The fixed carbon concentration is also a key indicator for evaluating biochar quality. The fixed carbon concentrations of the biochars produced under different pyrolysis conditions did not fluctuate substantially, ranging from 38.46% to 44.02%.

Moreover, the fixed carbon concentration did not increase continuously as the temperature rose from 550 via 600 to 650 °C. It even decreased under the combined condition of updraft and a high air distribution rate. This is in contrast to the phenomenon that the fixed carbon content of biochar produced by externally heated slow pyrolysis increases continuously with increasing pyrolysis temperature[23]. This may be because a higher pyrolysis temperature results in higher devolatilization and increased carbon combustion and gasification reactions under internally heated pyrolysis conditions. Furthermore, although the reforming reaction in downdraft pyrolysis consumes more carbon, this process is substantially longer than that in updraft pyrolysis, allowing for deeper devolatilization.

Atomic ratio

As shown in Fig. 3, a van Krevelen diagram was adopted to evaluate the quality of biochar carbonisation. The O/C and H/C atomic ratios of biochars produced under different pyrolysis conditions were 0.61–0.33 and 0.15–0.03, respectively. Like the fixed carbon concentration, the atomic ratios did not decrease as the pyrolysis temperature rose from 550 via 600 to 650 °C. The H/C molar ratio characterizes the performance of slow biomass pyrolysis, and 0.7 is regarded as the upper limit of the H/C molar ratio to ensure that biochar is suitable for carbon sequestration[23]. A low O/C molar ratio means stable carbon, and a ratio below 0.2 indicates an estimated half-life > 1,000 years[24].

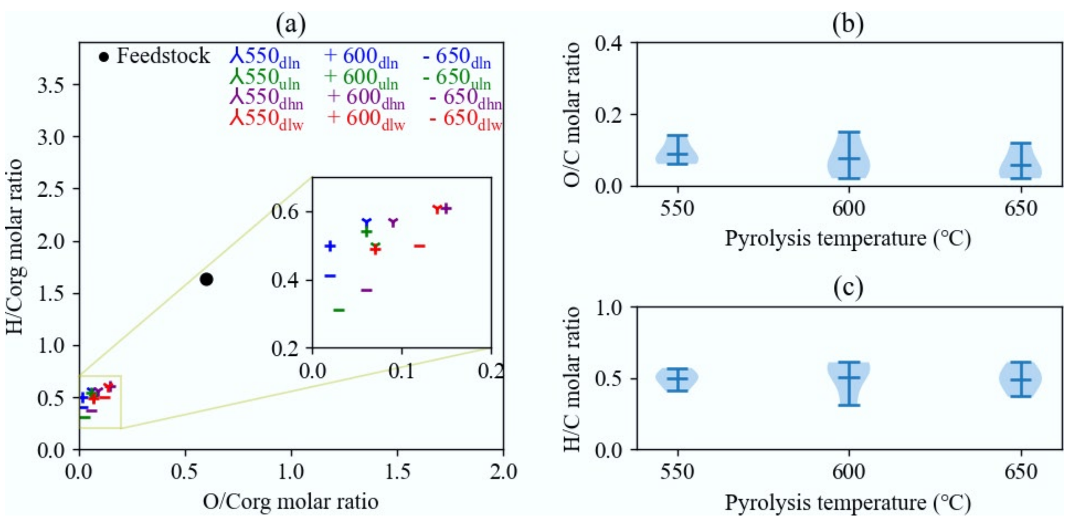

Fig. 3 (**a**) Van Krevelen diagram for pellets and their products. (**b**), (**c**) Probability density of O/C and H/C molar ratios.

The results indicated that long half-lives were expected for all biochars in this study, which would benefit carbon sequestration[25].

Functional properties of biochar

Specific surface area

The SSA is a functional factor of biochar for amending and improving soil. Figure 4 shows the SSA of biochars under different pyrolysis conditions, which ranged from 2.48 to 15.56 m^3/g. Owing to their beneficial pore structure and SSA, biochar composites have great potential for removing soil pollutants[26]. In our study, the SSA of biochar increased continuously as the pyrolysis temperature rose from 550 via 600 to 650 °C, consistent with related studies' conclusions[27].

The SSA of biochars decreased to different extents under updraft or downdraft conditions, with a high or low air distribution rate, and with water cooling or air insulation. For example, when the pyrolysis temperature was 650 °C, the SSA values of biochars derived under downdraft, low air distribution rate, and air insulation conditions were 1.46, 2.26, and 3.00 times higher than those under updraft, high air distribution rate, and water cooling conditions, respectively. Changes in the above pyrolysis conditions affect the residence time to different extents, and the residence time is positively correlated with the SSA[16].

pH value

Most biochars are alkaline, which can reduce the content of exchangeable hydrogen ions or aluminium ions in the soil and improve soil acidification. Figure 4 shows that the pH values of biochars derived from different conditions fluctuated from 7.3 to 9.0, lower than those derived from crop straw[23]. Generally, biochar pH increased continuously as pyrolysis temperature rose from 550 via 600 to 650 °C, indicating that carbonate and crystalline carbonate accumulation increased[27]. At the same pyrolysis temperature, biochar pH decreased to different extents under updraft or downdraft conditions, with a high or low air distribution rate and water cooling or air insulation. This may be partly because the biochar residence time decreased to different degrees with changes in the above pyrolysis conditions and was positively correlated with the accumulation of carbonate and crystalline carbonate in the biochar.

Cation exchange capacity

The CEC is also an important characteristic of biochar used for improving soil, as it reflects the capacity for nutrient retention and the level of anti-acidification[28]. The CEC showed no clear trends according to different pyrolysis conditions (Fig. 5); however, updraft conditions, a high air distribution rate, and water cooling generally improved the CEC of biochar. The CEC values of biochar produced under different pyrolysis conditions ranged from 12.03 to 59.70 cmol/kg, with an average value of 37.05 cmol/kg, which is lower than those of biochar derived from rice straw using external heating[23], but substantially higher than those of soil[29]. This study's high CEC of biochar indicates its potential for improving soil fertility.

Electrical conductivity

The EC is defined as the total amount of salt in the soil, which reflects nutrient availability and soil texture. The EC values of biochars produced under different pyrolysis conditions (Fig. 5) ranged from 176 to 293 μs/cm. The ideal EC values for plant growth are typically between 0.15 and 0.6 ms/cm[30], and should not exceed 2.5 ms/cm because overly high concentrations of soluble salts can damage plants or cause root death. Although EC changes showed no clear trends according to different pyrolysis conditions, they were consistent with the crop growth requirements, indicating that the biochars produced in the above conditions can be directly applied in agricultural cultivation.

Cleanliness properties of biochar

Concentration of PAHs

Sixteen priority PAHs associated with biochar are regulated by the US-EPA[31] and used to evaluate the cleanliness of biochars in this study. Figure 6 shows the PAH concentrations for biochars produced under different conditions. Like other studies, a relatively high proportion of PAHs included naphthalene, phenanthrene, fluorene, and acenaphthene[32]. PAH concentrations fluctuated from 0.03 to 0.44 mg/kg, indicating that all were far below the threshold values for biochar specified by the IBI and European Biochar Certificate[33]. The PAH concentration decreased substantially as the pyrolysis temperature rose from 550 via 600 to 650 °C, except under water-cooled conditions. This may indicate that a higher percentage of PAHs

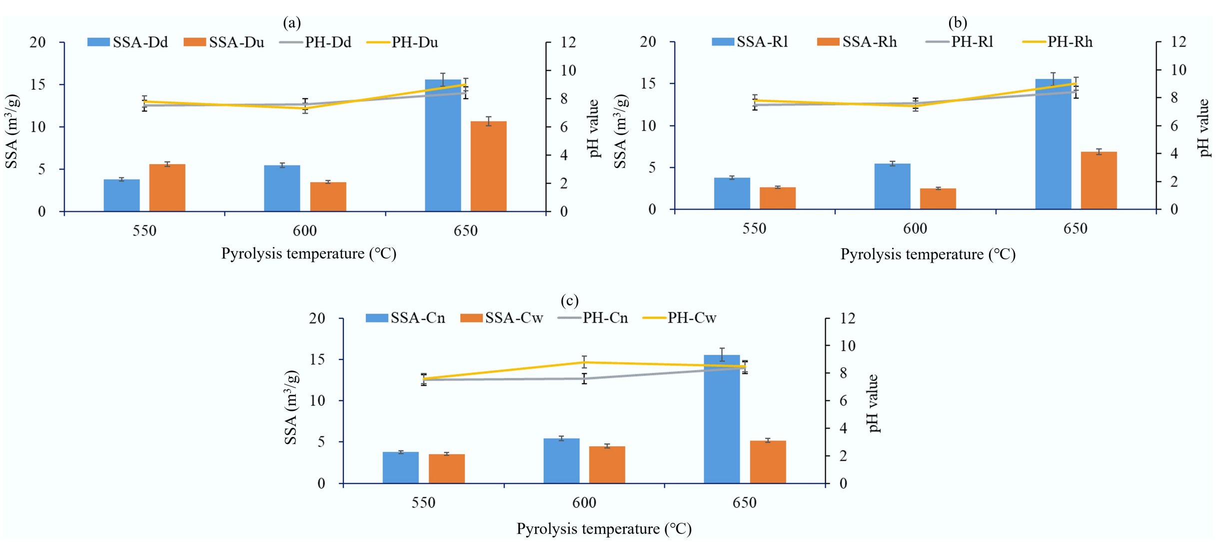

Fig. 4 Influence of (**a**) draft direction, (**b**) air distribution rate, and (**c**) cooling type at different pyrolysis temperatures on the specific surface area (SSA) and pH of biochar. Dd: downdraft condition, Du: updraft condition, Rl: low air distribution rate, Rh: high air distribution rate, Cn: air insulation, Cw: water cooling.

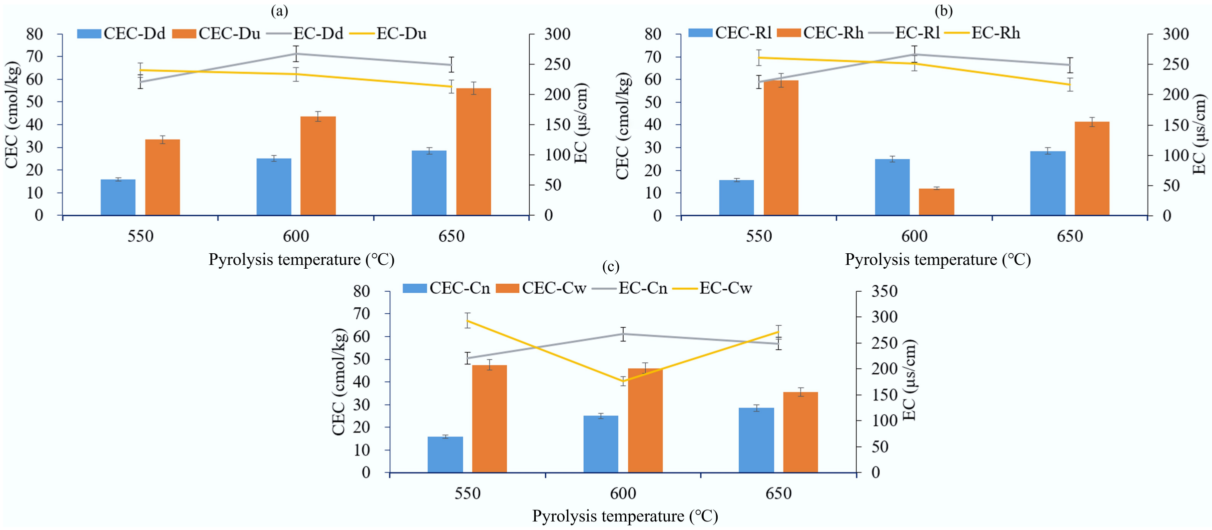

Fig. 5 Influence of (**a**) draft direction, (**b**) air distribution rate, and (**c**) cooling type at different pyrolysis temperatures on the cation exchange capacity (CEC) and electrical conductivity (EC) of biochar. Dd: downdraft condition, Du: updraft condition, Rl: low air distribution rate, Rh: high air distribution rate, Cn: air insulation, Cw: water cooling.

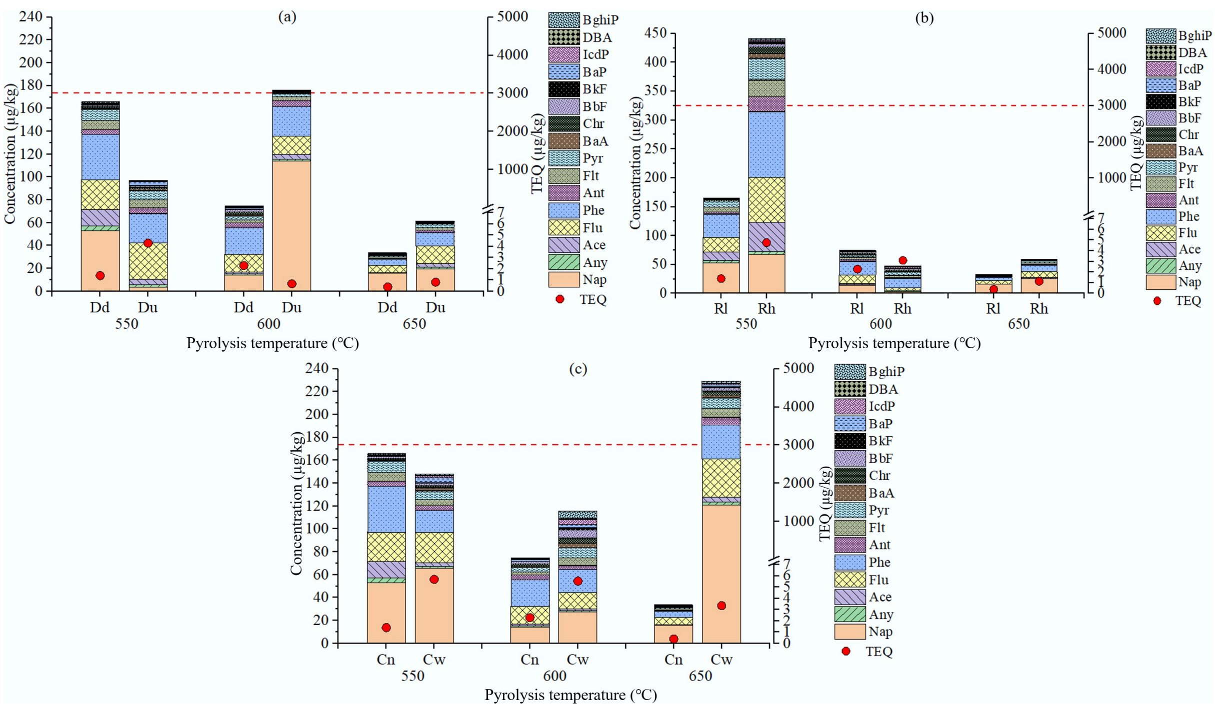

Fig. 6 Influence of (**a**) draft direction, (**b**) air distribution rate, and (**c**) cooling type on the polycyclic aromatic hydrocarbon (PAH) content and toxic equivalence quantity (TEQ) of biochar. Dd: downdraft condition, Du: updraft condition, Rl: low air distribution rate, Rh: high air distribution rate, Cn: air insulation, Cw: water cooling.

evaporated at a higher pyrolysis temperature. However, high temperatures can also accelerate PAH production. The PAH concentrations of biochars were substantially higher under water cooling conditions and at a high air distribution rate. At a pyrolysis temperature of 550 °C, the PAH concentration at a high air distribution rate was 2.66 times that at a low rate; at a pyrolysis temperature of 650 °C, the PAH concentration with water cooling was 6.89 times that with air insulation. Moreover, the PAH concentration of biochar derived from our novel internally heated cigar-type pyrolyzer was substantially lower than that of rotary, tubular, and kiln pyrolysis systems[32], indicating that a suitable reactor and optimized process can produce much lower PAH levels.

Toxicity analysis

The TEQ ranged from 0.39 to 5.68 μg/kg (Fig. 6), which was far below the IBI threshold (3 mg/kg) for biochar[33], indicating the premium cleanliness of the biochars obtained in this study. The variation in TEQ values according to different pyrolysis conditions was similar to the PAH concentration.

Biochar conversion efficiency

Energy conversion efficiency

The low heating values (LHVs) and energy yield rates of biochar and syngas were detected and calculated, as shown in Fig. 7. The LHVs of

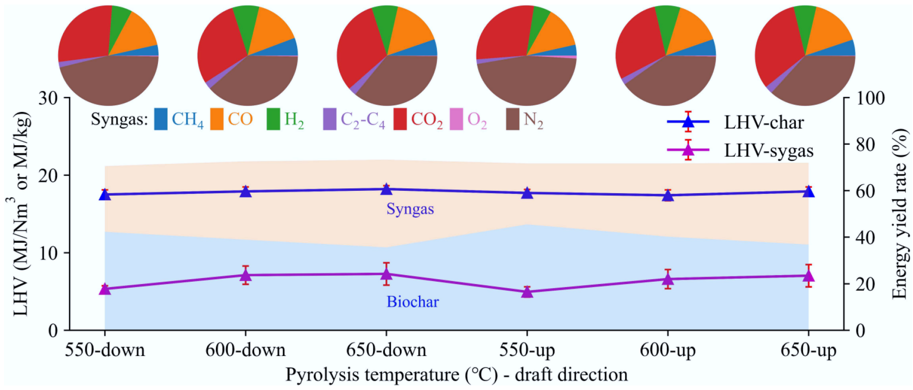

Fig. 7 Low heating value and energy distribution of biochar and syngas under different pyrolysis conditions.

the biochar fluctuated slightly, ranging from 16.69 to 17.33 MJ/kg. The LHVs of syngas increased as pyrolysis temperature rose from 550 via 600 to 650 °C, ranging from 5.33 to 7.27 MJ/Nm^3; these values were higher than those for biomass gasification technology[34]. The slow internal heating pyrolysis process adopted by our cigar-type pyrolyzer includes two chemical reactions, pyrolysis and gasification, which help improve the LHV of the syngas. The average energy conversion efficiency was approximately 75.31%, higher than that of external heating pyrolysis technology using a rotary kiln.

Comprehensive assessment

In summary, the updraft process showed certain advantages regarding the CEC, energy conversion efficiency, and equipment production capacity. The updraft process exploits the waste heat of the combustion and pyrolysis sections to dry the upper-layer materials; however, because part of the water vapour condenses in the upward process, the biomass pellet is soaked and smashed, which has a serious adverse effect on biochar quality. Moreover, the downdraft process was advantageous for the SSA of biochar in this study. The purpose of setting a high air distribution rate and water cooling is to improve the production capacity. However, these conditions increase the heating rate and reduce the residence time of biochar, which has a notable adverse impact on the SSA and cleanliness properties of biochar. Although the biochars produced by internal heating cigar-type pyrolysis showed good comprehensive performance, there is still a critical step to consider in the performance requirements of biochar for different applications, coordinate the conversion efficiency, and optimize the process parameters to determine the ideal conditions.

Conclusions

We developed a novel cigar-type slow pyrolysis apparatus with internal heating, using reed straw pellets as feedstock. This study systematically investigated the effects of draft direction, pyrolysis temperature, air distribution rate, and cooling type on the conventional, functional, cleanliness indices, and approximate conversion efficiency of biochar.

(1) Regarding the conventional properties, the fixed carbon content varied with pyrolysis conditions (38.46%–44.02%) and was substantially lower than that of slow pyrolysis technology with external heating. The H/C and O/C atomic ratios also fluctuated with pyrolysis conditions (0.61–0.33 and 0.15–0.03, respectively) and did not exhibit a persistent decrease with increasing pyrolysis temperature.

(2) Regarding the functional properties, the pyrolysis conditions strongly influenced SSA and CEC. At a pyrolysis temperature of 650 °C, the SSA values of biochars derived under downdraft conditions, with a low air distribution rate and air insulation, were 1.46, 2.26, and 3.00 times those of biochar derived under updraft conditions, with a high air distribution rate and water cooling, respectively. Overall, updraft conditions, high air distribution rates, and water cooling improved the CEC of biochar.

(3) Regarding the cleanliness properties, the TEQs of biochar fluctuated with pyrolysis conditions (0.39–5.68 μg/kg). Still, they were far below the IBI threshold (3 mg/kg), indicating the premium cleanliness of the obtained biochar. The PAH concentration increased substantially with a high air distribution rate and water cooling.

Ethical statements

Not applicable.

Author contributions

The authors confirm their contributions to the paper as follows: All authors contributed to the study conception and design. Hongbin Cong: writing − original draft. Mingsong Chen and Wei Song: material preparation, data collection, and analysis. Jiejie Fang and Bengang Ma: review. Jiaming An: material preparation, data collection, and analysis. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

All data generated or analyzed during this study are included in this published article.

Funding

This work was supported by the National Key Research and Development Project (Grant No. 2024YFD170110401).

Acknowledgments

This work was supported by the Key Laboratory of Energy Resource Utilization from Agriculture Residue, MARA, China.

Declarations

Competing interests

The authors declared that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential competing interest.

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References

[1] Pahnila M, Koskela A, Sulasalmi P, Fabritius T. 2023. A review of pyrolysis technologies and the effect of process parameters on biocarbon properties. *Energies* 16(19):6936

[2] Yang Q, Mašek O, Zhao L, Nan H, Yu S, et al. 2021. Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation. *Applied Energy* 282:116275

[3] Kambo HS, Dutta A. 2015. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renewable and Sustainable Energy Reviews* 45:359−378

[4] Cong H, Meng H, Chen M, Song W, Xing H. 2023. Co-processing paths of agricultural and rural solid wastes for a circular economy based on the construction concept of "zero-waste city" in China. *Circular Economy* 2(4):100065

[5] Wang J, Xiong Z, Kuzyakov Y. 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy* 8:512−523

[6] Tripathi M, Sahu JN, Ganesan P. 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: a review. *Renewable and Sustainable Energy Reviews* 55:467−481

[7] Keskinen R, Hyväluoma J, Sohlo L, Help H, Rasa K. 2019. Fertilizer and soil conditioner value of broiler manure biochars. *Biochar* 1(3):259−270

[8] Sakhiya AK, Anand A, Kaushal P. 2020. Production, activation, and applications of biochar in recent times. *Biochar* 2(3):253−285

[9] Liu L, Fan S, Zhang X, Gu K. 2020. Content and toxicity characteristics of polycyclic aromatic hydrocarbons in biochars derived from sewage sludge and rice straw. *Ecology and Environmental Science* 29(9):1874−1882

[10] Mahler BJ, Van Metre PC, Crane JL, Watts AW, Scoggins M, et al. 2012. Coal-tar-based pavement sealcoat and PAHs: implications for the environment, human health, and stormwater management. *Environmental Science & Technology* 46:3039−3045

[11] Zhang C, Zeng G, Huang D, Lai C, Chen M, et al. 2019. Biochar for environmental management: mitigating greenhouse gas emissions, contaminant treatment, and potential negative impacts. *Chemical Engineering Journal* 373:902−922

[12] Gómez N, Rosas JG, Cara J, Martínez O, Alburquerque JA, et al. 2016. Slow pyrolysis of relevant biomasses in the Mediterranean basin. Part 1. Effect of temperature on process performance on a pilot scale. *Journal of Cleaner Production* 120:181−190

[13] Ippolito JA, Cui L, Kammann C, Wrage-Mönnig N, Estavillo JM, et al. 2020. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar* 2:421−438

[14] Xiao H, Lin Q, Li G, Zhao X, Li J, et al. 2022. Comparison of biochar properties from 5 kinds of halophyte produced by slow pyrolysis at 500 °C. *Biochar* 4:12

[15] Shen X, Meng H, Shen Y, Ding J, Zhou H, et al. 2022. A comprehensive assessment on bioavailability, leaching characteristics and potential risk of polycyclic aromatic hydrocarbons in biochars produced by a continuous pyrolysis system. *Chemosphere* 287:132116

[16] Sieradzka M, Kirczuk C, Kalemba-Rec I, Mlonka-Mędrala A, Magdziarz A. 2022. Pyrolysis of biomass wastes into carbon materials. *Energies* 15:1941

[17] Campion L, Bekchanova M, Malina R, Kuppens T. 2023. The costs and benefits of biochar production and use: a systematic review. *Journal of Cleaner Production* 408:137138

[18] Campuzano F, Brown RC, Martínez JD. 2019. Auger reactors for pyrolysis of biomass and wastes. *Renewable and Sustainable Energy Reviews* 102:372−409

[19] Cong H, Meng H, Mašek O, Yao Z, Li L, et al. 2022. Comprehensive analysis of industrial-scale heating plants based on different biomass slow pyrolysis technologies: product property, energy balance, and ecological impact. *Cleaner Engineering and Technology* 6:100391

[20] Ni N, Li X, Yao S, Shi R, Kong D, et al. 2021. Biochar applications combined with paddy-upland rotation cropping systems benefit the safe use of PAH-contaminated soils: from risk assessment to microbial ecology. *Journal of Hazardous Materials* 404:124123

[21] Wang J, Odinga ES, Zhang W, Zhou X, Yang B, et al. 2019. Polyaromatic hydrocarbons in biochars and human health risks of food crops grown in biochar-amended soils: a synthesis study. *Environment International* 130:104899

[22] Karamarkovic R, Karamarkovic V. 2010. Energy and exergy analysis of biomass gasification at different temperatures. *Energy* 35(2):537−549

[23] Song W, Chen M, Xing H, Meng H, Cong H. 2023. Effect and evaluation of reaction conditions on the slow pyrolysis products of rice straw. *Transactions of the Chinese Society of Agricultural Engineering* 39(18):218−225

[24] Spokas KA. 2010. Review of the stability of biochar in soils: predictability of O:C molar ratios. *Carbon Management* 1(2):289−303

[25] Premchand P, Demichelis F, Chiaramonti D, Bensaid S, Fino D. 2023. Study on the effects of carbon dioxide atmosphere on the production of biochar derived from slow pyrolysis of organic agro-urban waste. *Waste Management* 172:308−319

[26] Pan X, Gu Z, Chen W, Li Q. 2021. Preparation of biochar and biochar composites and their application in a Fenton-like process for wastewater decontamination: a review. *Science of The Total Environment* 754:142104

[27] Chen F, Xia H, Liu F, Kong W, Lu S. 2022. Characteristics of biochar and its effects and mechanism on soil properties. *Journal of Environmental Engineering Technology* 12:161−172

[28] Antonangelo JA, Zhang H, Sun X, Kumar A. 2019. Physicochemical properties and morphology of biochars as affected by feedstock sources and pyrolysis temperatures. *Biochar* 1:325−336

[29] Laird DA, Fleming P, Davis DD, Horton R, Wang B, et al. 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* 158(34):443−449

[30] Zhao Y, Li M, Zhang J. 2009. Correlation between soil electrical conductivity and winter wheat yield. *Transactions of the Chinese Society of Agricultural Engineering* 25:34−37

[31] Massalha H, Korenblum E, Tholl D, Aharoni A. 2017. Small molecules below-ground: the role of specialized metabolites in the rhizosphere. *The Plant Journal* 90(4):788−807

[32] Han H, Buss W, Zheng Y, Song P, Khalid Rafiq M, et al. 2022. Contaminants in biochar and suggested mitigation measures – a review. *Chemical Engineering Journal* 429:132287

[33] Buss W, Graham MC, MacKinnon G, Mašek O. 2016. Strategies for producing biochars with minimum PAH contamination. *Journal of Analytical and Applied Pyrolysis* 119:24−30

[34] Trninić M, Stojiljković D, Manić N, Skreiberg Ø, Wang L, et al. 2020. A mathematical model of biomass downdraft gasification with an integrated pyrolysis model. *Fuel* 265:116867