

Waste biomass-derived biochar in adsorption-photocatalytic conversion of CO₂ for sustainable energy and environment: Evaluation, mechanism, and life cycle assessment

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ABSTRACT

Biochar is an environmentally friendly material with great potential for carbon capture and storage. As the first of its kind, waste biomass-derived biochar was utilized to convert CO₂ into fuel in solar. Herein, among four representatives herbaceous, woody, sludge, and manure wastes, the pine sawdust-derived biochar produced the highest CO assisted by higher CO₂ adsorption, more than 10 times higher than that of graphene and activated carbon. The function groups of carbonyl and carboxyl on biochar controlled the CO₂ capture and solar conversion by decreasing adsorption and activation energies of CO₂ molecules. The biochar performed even better for 15% CO₂/N₂ atmosphere, a typical CO₂ concentration in the flue gas, demonstrating its promising potential in waste gas resource utilization. The life-cycle assessment indicates that feedstock with more cellulose and lignin provide better environmental and economic benefits. The work highlights a sustainability pathway for waste biomass-derived biochar in CO₂-to-fuel under ambient conditions.

1. Introduction

With rapid economic development, bio-waste resources such as agriculture residuals, forestry residuals, industry byproducts, and animal wastes are continuously generated [1]. They are renewable and inexpensive, and thus are ideal feedstock for the production of biochar through pyrolysis in an inert atmosphere [2–4]. Owing to its large specific surface area, well-developed pore structure, high non-carbonized component content, abundant surface functional groups, cost-effectiveness, and sustainability, biochar has been widely applied in the field of energy storage, environmental remediation, catalysis [5–8]. As the CO₂ concentration in the atmosphere has exceeded 410 ppm with a continuous stable increase, carbon capture, storage and utilization (CCSU) become an indispensable need [9,10]. The waste biomass-derived biochar, as porous adsorbent, has attracted much attention in carbon capture to reducing CO₂ emission [9,11,12], but there is little research into their subsequent CO₂ conversion. On the

other hand, biochar has excellent electrochemical and catalytic properties [8,13,14], making it a promising agent for CO₂ conversion. It is thus worth of exploring of the application of biochar in CO₂ conversion, which can maximize the benefits of biochar for energy and environmental sustainability.

Comparing CCSU technologies, single adsorption technique involves the risk of secondary pollution, and adsorption-catalytic conversion is typically regarded as a highly efficient method for tackling the problem of CO₂ emissions. Among them, electrocatalysis, photoelectrocatalysis, thermocatalysis and photothermocatalysis possess certain fateful drawbacks, such as high cost and low stability [15]. However, the low-cost solar irradiation has been considered as a sustainable energy to promote CO₂ conversion to produce green and sustainable fuel to solve climate and energy crisis [16]. The functional groups on photocatalysts surface have been verified by numerous studies to strengthen adsorption and activation of CO₂ molecules, reduce the activation energy barrier, thereby speed up the surface catalytic reaction [16–19]. Biochar with

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multiple functional structures (oxygen-containing groups, persistent free radicals, defects, mineral components, etc.) is promising in the photocatalysis field [20–25]. For example, the dense aromatic structure of biochar can act as an electron shuttle to assist electron migration [26], and the intrinsic oxygenated functional groups are prone to be activated and excited to generate reactive oxygen species (ROS) [22]. In addition, their edge defects with delocalized π -electrons and minerals/organic carbon components are favorable to the reactant adsorption [21,24] and solar light absorption [25], respectively. Therefore, the above excellent characteristics of biochar make them promising catalysts for CO₂ solar conversion.

In the field of catalytic CO₂ conversion, metal-based catalyst materials are most commonly utilized. Zhao's team reported that the prepared metal-based catalysts (i.e., AuZn@ZnO, Zn^{δ+}/ZnO/CeO₂, Cu₂O/ZnO, α -Fe₂O₃/ZnO, etc.) manifested superior photocatalytic activity toward CO₂ conversion [27–31]. However, metal-based catalysts do not have great advantages in terms of cost, corrosion resistance, and stability, limiting their industrial applications [32,33]. Encouragingly, carbon-based materials with low cost and environmental friendliness including graphene, activated carbon, nanofibers, g-C₃N₄, carbon nanotubes and biochar offer certain complementary and emerging applications in catalyzing CO₂ reduction, which are usually in combination with other metallic and nonmetallic composites to enhance CO₂ uptake and conversion [34–36]. In particular, biochar has only been used as supporting materials for metal semiconductors or doped heteroatoms [37–41], which inevitably leads to increased cost and secondary

environmental pollution. If biomass-derived pristine biochar can serve as an effective photocatalyst for solar conversion of CO₂ to produce sustainable fuels, it would greatly improve the economic and sustainable viability of CCSU.

Herein, owing to unique characteristics of pine sawdust (PS) with more cellulose, hemicellulose and lignin, wheat straw (WS) with less inorganic compounds, sewage sludge (SS) with more mineral compositions, and cow manure (CM) with less organic compounds, the above four typical biomass wastes were selected as feedstocks for biochar production (Fig. 1A). They were pyrolyzed at relatively low temperatures (300–400 °C) to save energy based on the results of TG (Fig. S1). Furthermore, the waste biomass-derived biochar was applied in CO₂ solar conversion to sustainable fuels without any sacrificial/metal agents or heating conditions. The pine sawdust-derived biochar achieved the best CO fuel production of 39.9 $\mu\text{mol}\cdot\text{g}^{-1}$ from CO₂ photoreduction, which was more than 10 times higher than that of other advanced carbon materials (i.e., graphene and activated carbon). Comprehensive characterizations and density functional theory (DFT) calculations revealed the governing mechanism and the role of biochar in CO₂ solar conversion. Moreover, the effect of different CO₂ concentrations in environment and a life-cycle assessment (LCA) of CO fuel product were analyzed in detail to confirm the sustainability benefits. As the first of its kind, this study has opened a door to the potential applications of waste biomass-derived biochar in solar conversion of CO₂ into fuels for sustainable energy and environment.

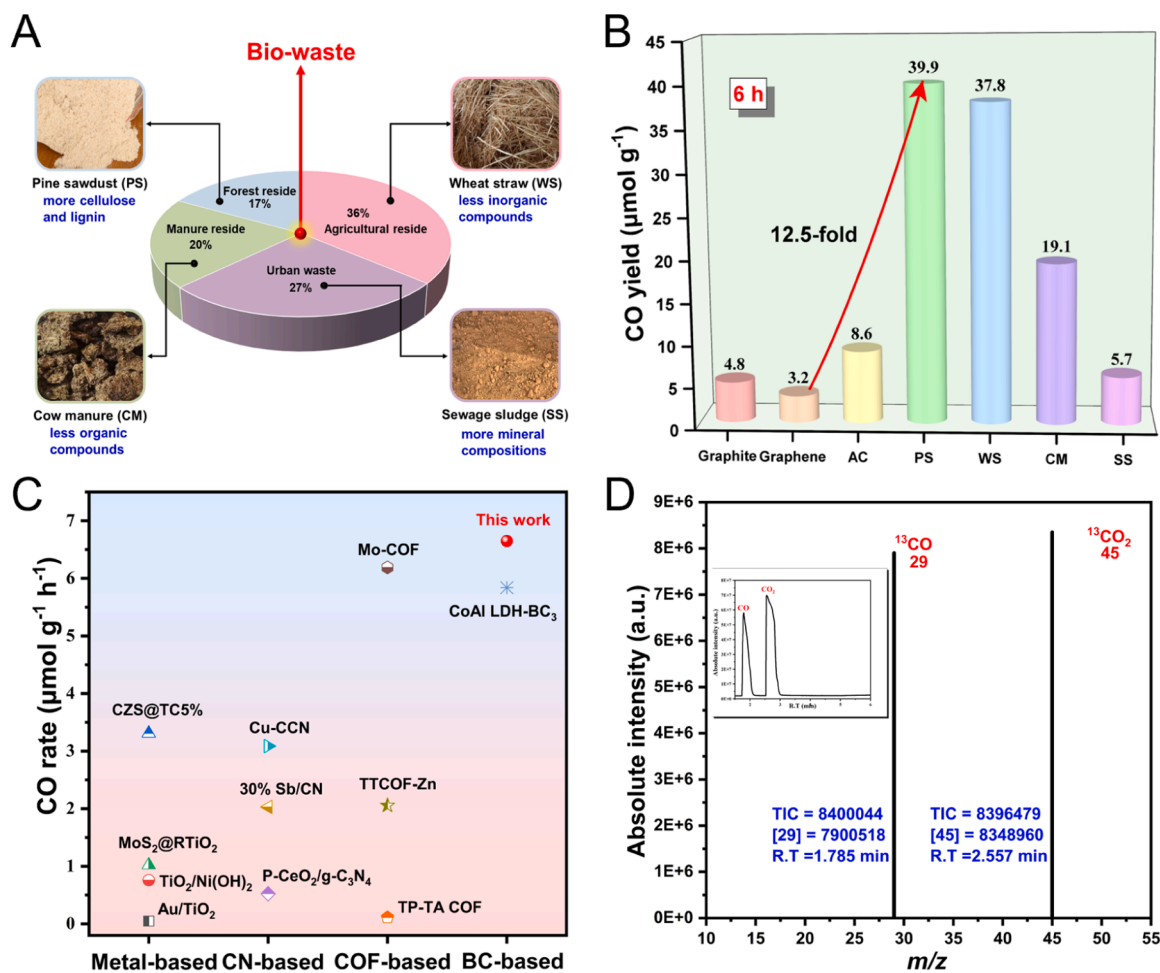


Fig. 1. (A) Composition of four bio-waste resources (based on the data of Wang et al. [47]). (B) Production of CO from CO₂ photoreduction by graphite, graphene, AC, and various waste-derived biochar under light illumination. (C) Comparison of CO evolution rate in solar conversion of CO₂ by PS350 (this work) to that of advanced metal or carbon based photocatalysts in previous studies. (D) GC-MS spectrum of the products of photocatalytic ¹³CO₂ reduction over PS350.

2. Materials and methods

2.1. Biochar production

PS, WS, SS, and CM waste biomass obtained from Jiangsu Liangyungang Changyuan straw processing plant, advanced farm, Chemical Baita Industrial Park were selected as the woody, herbaceous, sludge, and livestock manure feedstocks, respectively. The feedstock was ground and passed through 120 mesh sieves, then rinsed with deionized water and oven-dried for future use. For the preparation of biochar, the cleaned biomass powder was pyrolyzed in a tubular furnace (OTF-1200X-II) at a certain temperature with a heating rate of 5 °C/min for 3 h under N₂ atmosphere. The obtained black power was washed using deionized water to remove the impurities and air-dried for 12 h at 100 °C. The product was again dried in the oven at 180 °C for 24 h prior to use. The results of TG (Fig. S1) showed that the pyrolytic zone of the four-biomass ranged from about 200–400 °C, and 350 °C was thus chosen as the pyrolysis temperature to convert the four feedstocks into biochar, which were labeled as PS350, WS350, SS350, and CM350. Three different pyrolysis temperatures (300 °C, 350 °C, and 400 °C) were used to obtain three types of PS biochar (PS300, PS350, and PS400, respectively).

2.2. Characterization

Scanning electron microscopy (SEM) was conducted on an SSX-550 instrument. X-ray powder diffraction (XRD) analysis was operated by a Philips X'Pert Pro diffractometer under Ni-filtered Cu K α radiation. Fourier transform infrared (FT-IR) spectra were collected from a NICOLET iS10 FT-IR spectrometer. Thermogravimetry analysis (TGA) was taken on a STA 449 C instrument from indoor temperature to 950 °C with a heating rate of 5 °C/min in a purified N₂ atmosphere. N₂ and CO₂ adsorption and desorption isotherms were acquired from the Micro-metrics ASAP-2020 device at 77 K and room temperature, respectively. X-ray photoelectron spectroscopy (XPS) data were carried out using a PHI 5000 Versa Probe spectrometer with work function of 4.6 eV and calibrated using the adventitious C 1 s line at 284.6 eV. ¹³C magic-angle spinning nuclear magnetic resonance (MAS NMR) was measured on a Bruker Avance III spectrometer at 9.4 T and 100.6 MHz. Mineral elements of biochar were detected on an inductive coupled plasma (ICP) emission spectrometer (Avio500). Before the test, the mixture of the sample, nitric acid, hydrogen peroxide, and hydrochloric acid was transferred into a Teflon-lined autoclave and heated at 200 °C for 12 h. The UV–vis diffuse reflectance spectra (DRS) were obtained from a UV-3600 device. The electrochemical impedance spectroscopy (EIS), Mott-Schottky (M-S), and transient photocurrent response experiment were performed on a CHI660E electrochemical workstation with an Ag/AgCl reference electrodes in 0.1 M Na₂SO₄ as electrolyte solution. Boehm titration was used to quantify the surface oxygen-containing functional groups on biochar [42]. The method assumes that sodium ethoxide (C₂H₅ONa) can neutralize carboxylic, lactonic, phenolic hydroxyl, and carbonyl groups; sodium hydroxide (NaOH) can neutralize carboxylic, lactonic, and phenolic hydroxyl groups; sodium carbonate (Na₂CO₃) can neutralize carboxylic, and lactonic groups; sodium bicarbonate (NaHCO₃) only neutralizes carboxylic groups. 50 mg of sample was added into 25 mL of 0.05 M C₂H₅ONa, NaOH, Na₂CO₃, NaHCO₃, respectively, and shaken for 24 h. The content of various groups was determined by titrating the remaining base with 0.05 mol HCl. In situ diffuse reflectance infrared Fourier transform spectra (DRIFTS) for the adsorption and photocatalytic reduction processes of CO₂ and H₂O were recorded with a Nicolet Nexus 5700 FTIR spectrometer. The sample was filled into the infrared cell and pretreated at 200 °C in purified N₂ for 1 h, then kept to 30 °C. Thereafter, water vapor is brought into the reaction cell in the form of a bubble of CO₂ gas (pure CO₂ and 15% CO₂/N₂). The adsorption and photocatalytic DRIFTS data were collected for 1 h in dark and under the 280 W Xe lamp irradiation, respectively.

2.3. Computational methodology

Different oxygen-containing functional groups (carboxyl, carbonyl, hydroxyl, and lactones groups) by grafting or substituting C and H atoms are constructed on the edges of coronene that was chosen as the basic structure of the carbonaceous skeleton of the biochar, which is an acknowledged model reported previously in the literature [43]. Theoretical models were exploited to calculate its adsorption and activation capability for CO₂. The calculations in this work are performed using the DMol3 scheme [44], which is fully optimized based on DFT calculations. Perdew-Burke-Ernzerhof (PBE) functional in the generalized gradient approximation (GGA) was chosen to describe the exchange correlation potential [45]. The Tkatchenko and Scheffler (TS) scheme was used to correct for the influence of van der Waals (vdW) forces [46]. The total energy was set to 1 × 10⁻⁵ Ha (Hartree) with 1 × 1 × 1 Monkhorst-pack k-points grid. The tolerance of residual force was set as 0.002 Ha/Å. The maximum displacement below 0.005 Å was set as the convergence thresholds in geometry optimization.

2.4. Evaluation of photocatalytic CO₂ reduction

The photocatalytic CO₂ reduction was tested in a closed system under 280 W Xe lamp irradiation. Specifically, 10 mg of BC samples were added into 1 mL of deionized water and ultrasounded for 0.5 h, then uniformly dispersed on a quartz sand plate ware with a diameter of 4.2 cm, placed in a 100 mL stainless steel reactor. High purity CO₂ or 15% CO₂/N₂ was filled into the reactor up to 0.2 MPa and irradiated for 6 h after dark treatment for 1 h. The product CO was detected and analyzed by online gas chromatography (GC-7920) periodically (1 h). The CO yield (Y_{CO}) was calculated by the following formula:

$$Y_{CO} = \frac{A_t[CO]_s P_r V_r}{A_s R T_r m_{cat}}$$

where A_t is the peak area of CO at time t; A_s and [CO]_s represent peak area and concentration (ppm) of the CO standard gas, respectively; R is molar gas constant; P_r, V_r, and T_r are the pressure, gas volume, and temperature inside the reactor, respectively; m_{cat} is the mass of the photocatalyst biochar.

3. Results and discussion

3.1. Adsorption-photocatalytic conversion CO₂-to-CO

The waste biomass-derived pristine biochar prepared at 350 °C were used in the reaction of CO₂ conversion by solar with full-spectrum without the addition of any metals or sacrificial agents, or heating. All four biochar demonstrated the ability of solar conversion of CO₂ to CO fuel, and PS-derived biochar exhibited the highest CO production of 39.9 μmol·g⁻¹ in 6 h with the assistance of higher CO₂ adsorption capacity (Fig. S2), which was about 13 and 5 times higher than that of graphene and activated carbon (AC), respectively (Fig. 1B). Particularly, in comparison to previous studied metal and carbon-based advanced materials (e.g., g-C₃N₄ (CN), COF, and biochar (BC)), the waste biomass-derived biochar performed much better in the solar conversion of CO₂ to CO (Fig. 1C and Table S1). Even under the normal pressure (NP) reaction conditions, the PS350 can still display a favorable CO generation yield in 6 h (28.4 μmol·g⁻¹, Fig. S3). What's more, no significant decay was observed in the CO yield of PS350 catalyst in cycle tests (Fig. S4), highlighting its superior stability and practical application potential. In order to confirm the CO fuel was a product from CO₂ instead of biochar, ¹³CO₂ was used in the solar conversion experiment to trace the product source (Fig. 1D). In the GC-MS spectrum, peaks at m/z = 45 and 29 correspond to the fragments of ¹³CO₂ and ¹³CO, respectively. This confirmed the exclusive formation of the evolved CO from the reduction of CO₂, rather than from the decomposition of the biochar. Therefore,

waste biomass-derived biochar is an effective and sustainable catalyst for solar conversion of CO₂.

3.2. Mechanism exploration

The unique catalytic performances of biochar are often ascribed to their mineral elements and functional groups, and mineral elements are closely related to the biomass feedstocks. Herein, in four biochar samples of PS, WS, CM and SS at different pyrolysis temperatures (300 °C, 350 °C, 400 °C), their main mineral elements of Al, Fe, Mg, Ca, Mn, P, Si, Na, K were determined by the ICP method (Table S2). The corresponding relationships between the mineral elements and CO yield are shown in Figs. 2 and S5. After a simple correlation analysis with Pearson's product-moment correlation coefficient (r), it was observed that there were no positive correlations between mineral elements and CO yields from CO₂ reduction ($r = -0.43$, $R^2 = 0.18$, Fig. 2A), revealing that not all of biochar's functional structures, i.e., mineral components, exhibit catalytic activity for CO₂ conversion. The weak negative correlation ($0 \leq R^2 < 0.3$) phenomenon presented by the CO generation from CO₂ reduction and mineral elements contributions may be attributed to the increase in surface polarity induced by endogenous minerals in the biochar inhibiting the adsorption and activation of CO₂ and H₂O molecules [48]. Among these elements, Al ($r_{Al} = -0.89$, $R^2_{Al} = 0.79$, Fig. 2B-C) and Fe ($r_{Fe} = -0.87$, $R^2_{Fe} = 0.76$, Fig. 2B and D) even presented strong negative correlations with the CO₂-to-CO rate. For the rest of the elements of Mg, Ca, Mn, P, Si, Na, K in the ash, there were no significant correlation ($R^2 < 0.5$) with the CO₂-to-CO rate (Figs. 2B and S5A-G).

Interestingly, the correlations between mineral elements and CO₂ adsorption capacity (Fig. S5H) are highly consistent with CO yields, which is attributed to the fact that except for Al and Fe elements in the form of sulfate, the rest of main mineral elements are existed in the forms of carbonates, bicarbonates, or chlorides in the ash of biochar, and the high content of soot particles would block the pores and occupy the adsorption sites of biochar, which are not conducive to CO₂ adsorption and reduction, reducing biochar's ability for CO₂ solar conversion [49–51]. These results indicate that metal elements in the waste biomass-derived biochar were not the important factors for solar conversion of CO₂.

Biochar's oxygen containing function groups are usually affected by the pyrolysis temperatures, and the PS-derived biochar prepared at different temperatures (i.e., PS300, PS350, and PS400) were used to investigate the relationship between function groups and CO fuel yield. All three PS-derived biochar samples exhibited the similar shapes (Fig. S6) and specific surface areas (Fig. S7). The band structures were examined by Mott-Schottky and valence band (VB) XPS methods (Figs. S8–11), showing that all the conduction bands (CB) of PS300 (-1.03 eV), PS350 (-1.06 eV), and PS400 (-1.01 eV) were more negative than the standard reduction potential of CO₂-to-CO (-0.53 eV) [52]. Therefore, they can thermodynamically convert CO₂ to CO (Fig. S12) following the order of PS350 > PS300 > PS400. Moreover, the XRD patterns (Fig. S13) and FT-IR spectra (Fig. S14, Table S3) suggested that with the increased carbonization temperature, the surface functional groups of biochar decreased but the aromaticity enhanced [53]. The XPS and Boehm titration techniques were combined to ascertain the

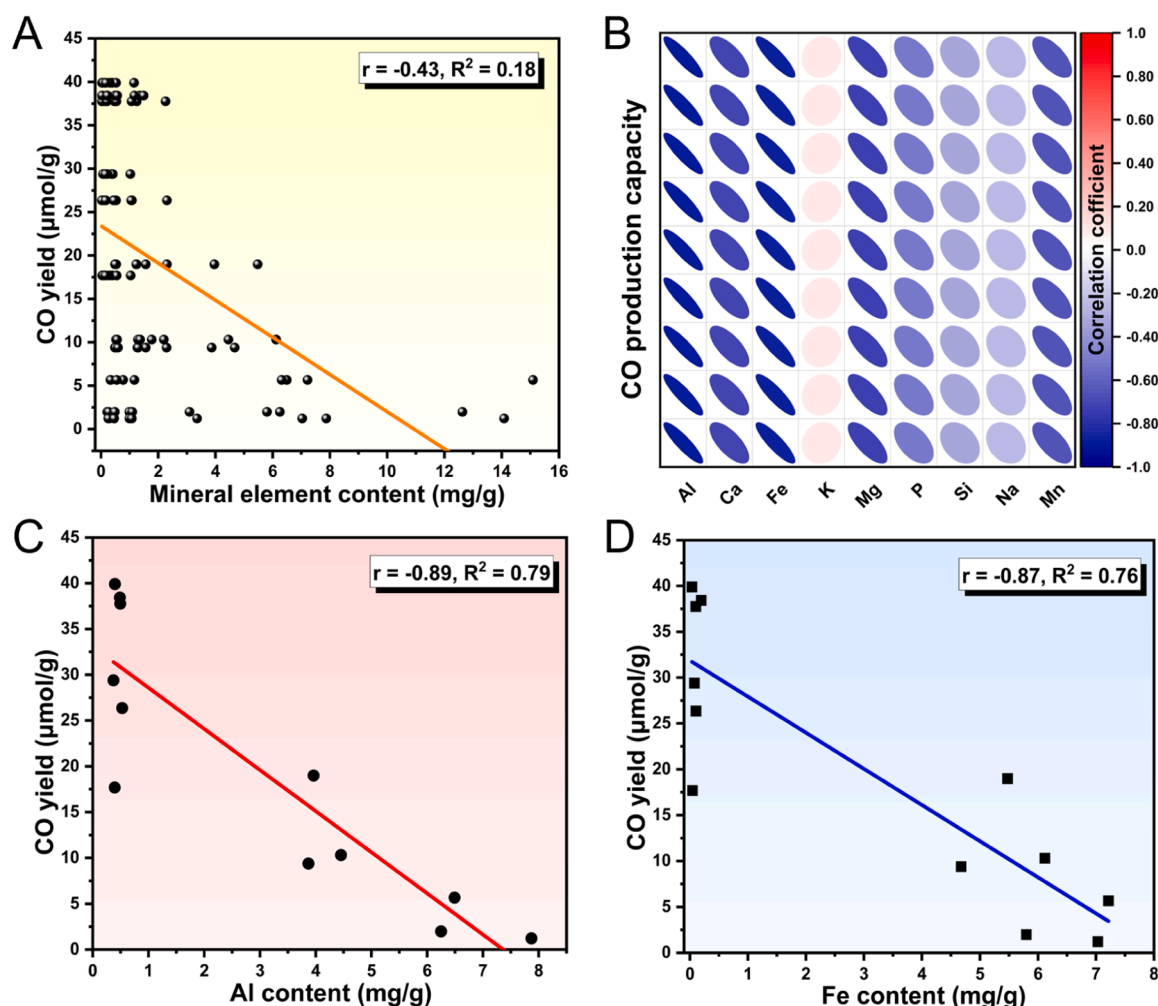


Fig. 2. Relationships between (A–B) all, (C) Al, (D) Fe mineral elements of biochar and CO yields from photocatalytic CO₂ conversion.

qualitative and quantitative information of functional groups of biochar. In high-resolution XPS spectra of C 1s illustrated in Fig. S15A, three characteristic peaks centered at about 288.7, 286.2, and 284.6 eV can be ascribed to O-C=O, C-O, and C-C/C=C groups, respectively [54]. The O 1s spectra (Fig. S15B) were fitted into three peaks with the binding energy values of 533.7 eV (H₂O/-OH), 532.9 eV (C=O), and 531.7 eV (C-OH/C-O-C) [55,56]. The details on the relative concentrations of the different types of groups are shown in Table S4 and Fig. 3A. In comparison to PS300 (37.49%, 4.74%) and PS400 (31.26%, 5.05%), PS350 (39.87%, 6.02%) had more C=O and O-C=O. In addition, the Boehm titration data (Fig. 3B) confirmed that the presence of a larger amount of carboxyl (-COOH) and carbonyl (C=O) groups in PS350 sample. Furthermore, the ¹³C NMR results of the PS350 samples before and after the photoreduction CO₂ reaction were measured (Fig. 3C and Table S5). The used PS350 sample displayed similar peaks as the fresh PS350, suggesting that the PS350 biochar was stable during the photocatalytic reaction. Interestingly, the relative intensities of the -COOH (178 ppm) and C=O (198 ppm) to others became weaker after the reaction [57, 58], suggesting that -COOH and C=O groups could act as the key reaction sites for the solar conversion of CO₂ to CO fuel.

The DFT calculation was carried out to validate the key role of function groups in CO₂-to-CO fuel, and the adsorption conformations and energies were calculated (Figs. S16–17 and Table S6). Unlike other

functional groups, -COOH group preferred to interact with O atom (CO₂ molecule) via the hydrogen bonds, exhibiting a smaller minimum adsorption distance (2.14 Å) than C=O group (2.94 Å). On the other hand, the p-electrons of O atom (C=O group) as Lewis base interacted with electron-deficient C atom (CO₂). Therefore, under the above interactions of hydrogen bonds and p-electrons, the bond polarization of CO₂ molecule was enhanced, leading to its activation, break, and reduction. Because of the lower adsorption energies of CO₂ on -COOH (-0.197 eV) than that on C=O (-0.346 eV) groups, the rate-determining step in CO₂ conversion was the generation of key *COOH intermediate. Furthermore, in situ DRIFTS of CO₂ adsorption was performed to explore the CO₂ activation on PS350. As depicted in Fig. 4A, once CO₂ reactant was applied, the peak (1538 cm⁻¹) corresponding to the monodentate carbonate species (m-CO₃²⁻) appeared [59]. Subsequently, the band (1706 cm⁻¹) related to *COO species generated [57], due to the stronger interaction between p-electrons of O atom (C=O group) and C atom (CO₂). All these are consistent with the DFT results. Afterward, the formation of HCO₃⁻ species (1648 cm⁻¹) was attributed to the synergistic interactions of hydrogen bonds (-COOH group) and p-electrons (C=O group) for CO₂ activation and reduction [60]. Therefore, PS350 biochar with the most abundant carbonyl and carboxyl groups exhibited the best ability of CO₂ solar conversion. Whereas, on PS300 (Fig. S18A), the peak intensities of intermediates were weaker than that of PS350, suggesting

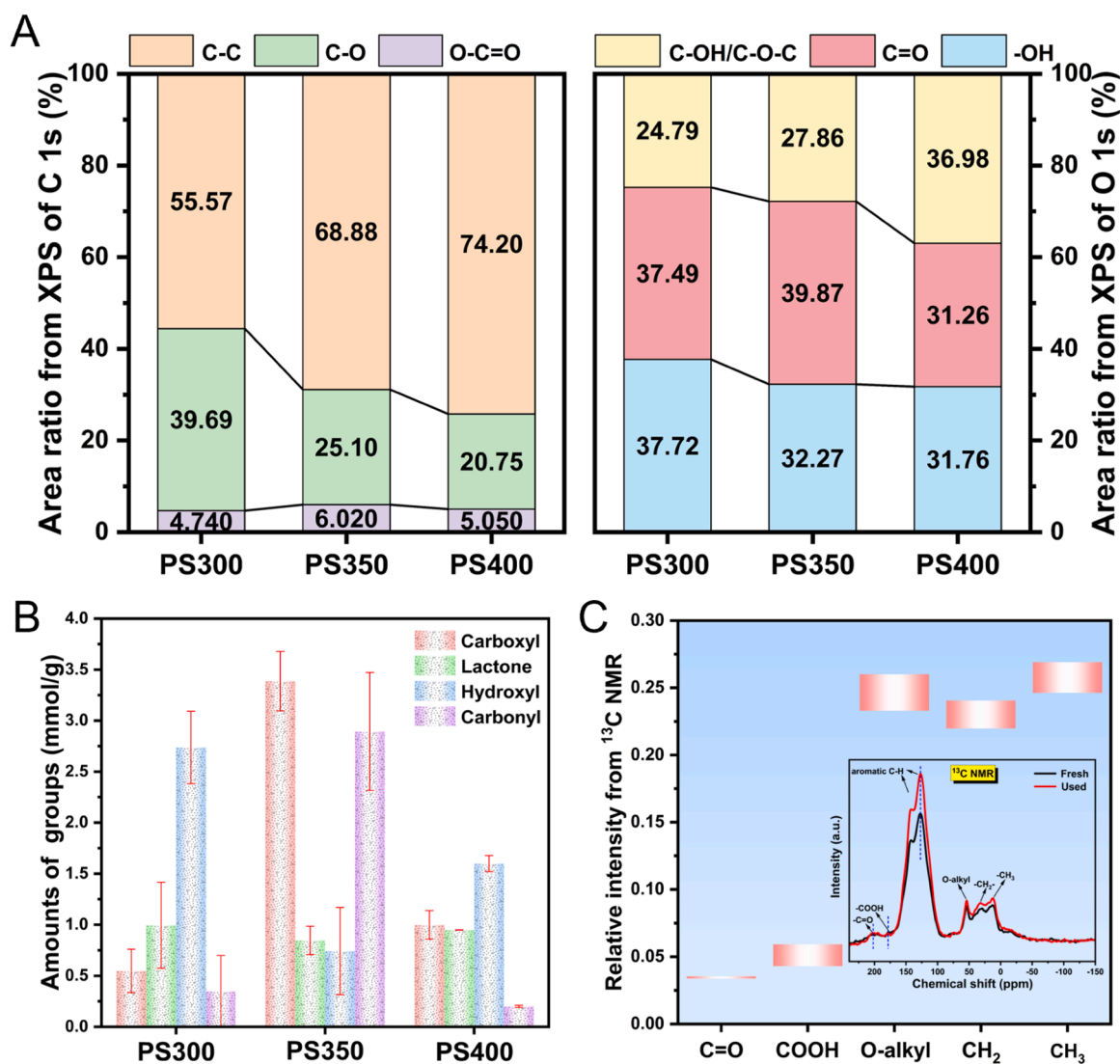


Fig. 3. (A) Area ratio plots from XPS of C 1s and O 1s. (B) Contents of various functional groups from Boehm titration of PS300, PS350, and PS400. (C) Change of group content of PS350 before and after photocatalytic CO₂ reduction (inset: ¹³C MAS NMR spectra of PS350 before and after).

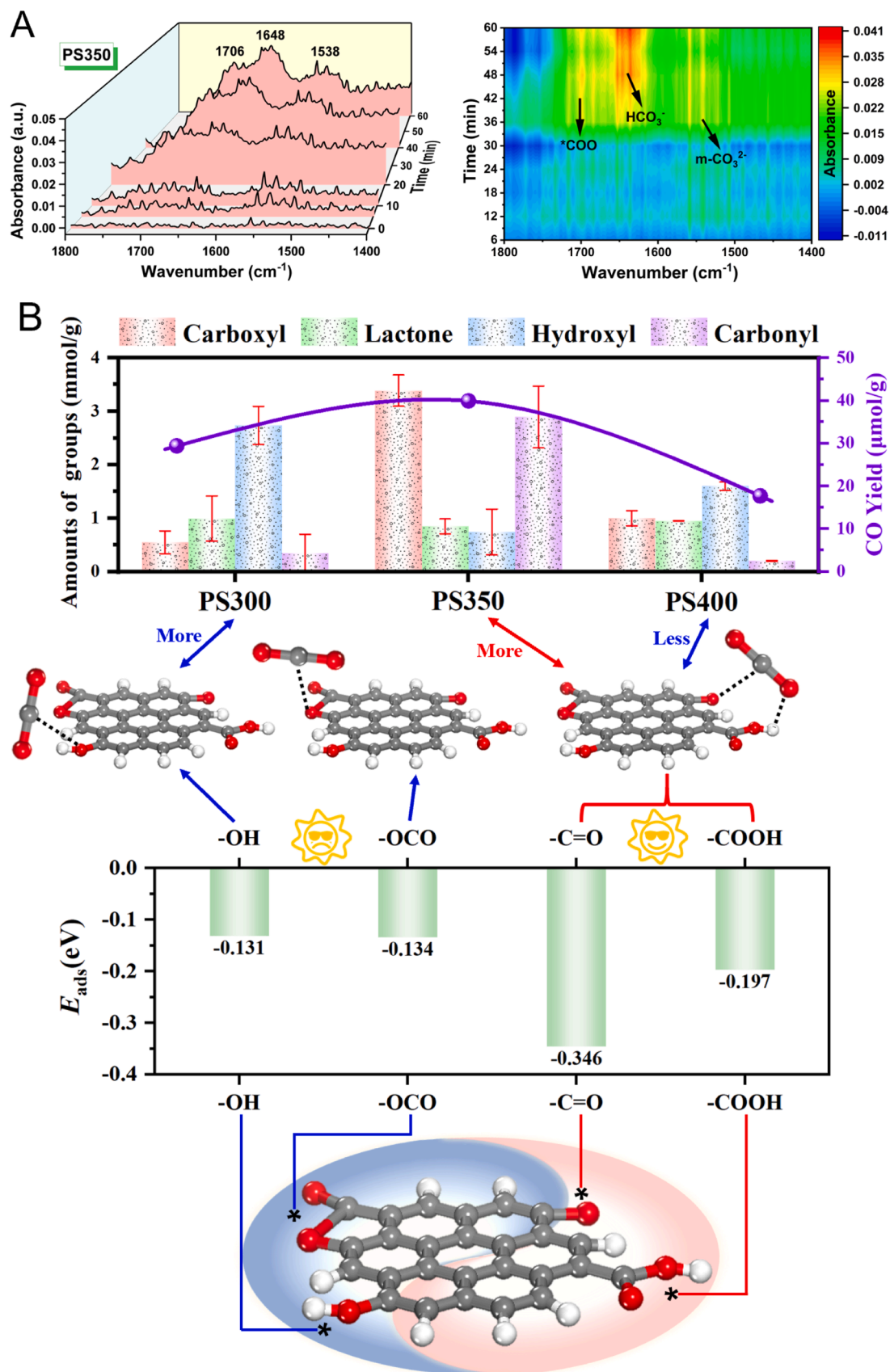


Fig. 4. (A) In situ DRIFTS of pure CO₂ and H₂O vapor co-adsorption on PS350 within 60 min at 30 °C in dark. (B) Schematics of the mechanism for CO₂ activation by different oxygen-containing functional groups on biochar.

that the phenolic hydroxyl groups on the PS300 surface were undesirable for the adsorption and activation of CO_2 . This is also consistent with the DFT calculations. For PS400 sample (Fig. S18B), only two weak peaks of $^*\text{COO}$ and m-CO_3^- species were observed, too few to activate CO_2 for the solar conversion.

On the basis of the qualitative and quantitative results of functional groups, the DFT calculations, and in situ characterizations, the governing mechanism of biochar enabled solar conversion of CO_2 can be

determined as follows. Owing to PS350's abundant carbonyl ($\text{C}=\text{O}$) and carboxyl ($-\text{COOH}$) groups, the bonds of CO_2 reactant could be activated and polarization, through the synergistic interactions of hydrogen bonds ($-\text{COOH}$ group) and p-electrons ($\text{C}=\text{O}$ group), leading to the subsequent solar conversion to CO fuel. Whereas more phenolic hydroxyl groups on the PS300 surface and fewer carboxyl groups on PS400 were poorer for CO_2 adsorption and conversion (Fig. 4B). In comparison with published studies on carbon-based materials supplied in Table S7, we identified

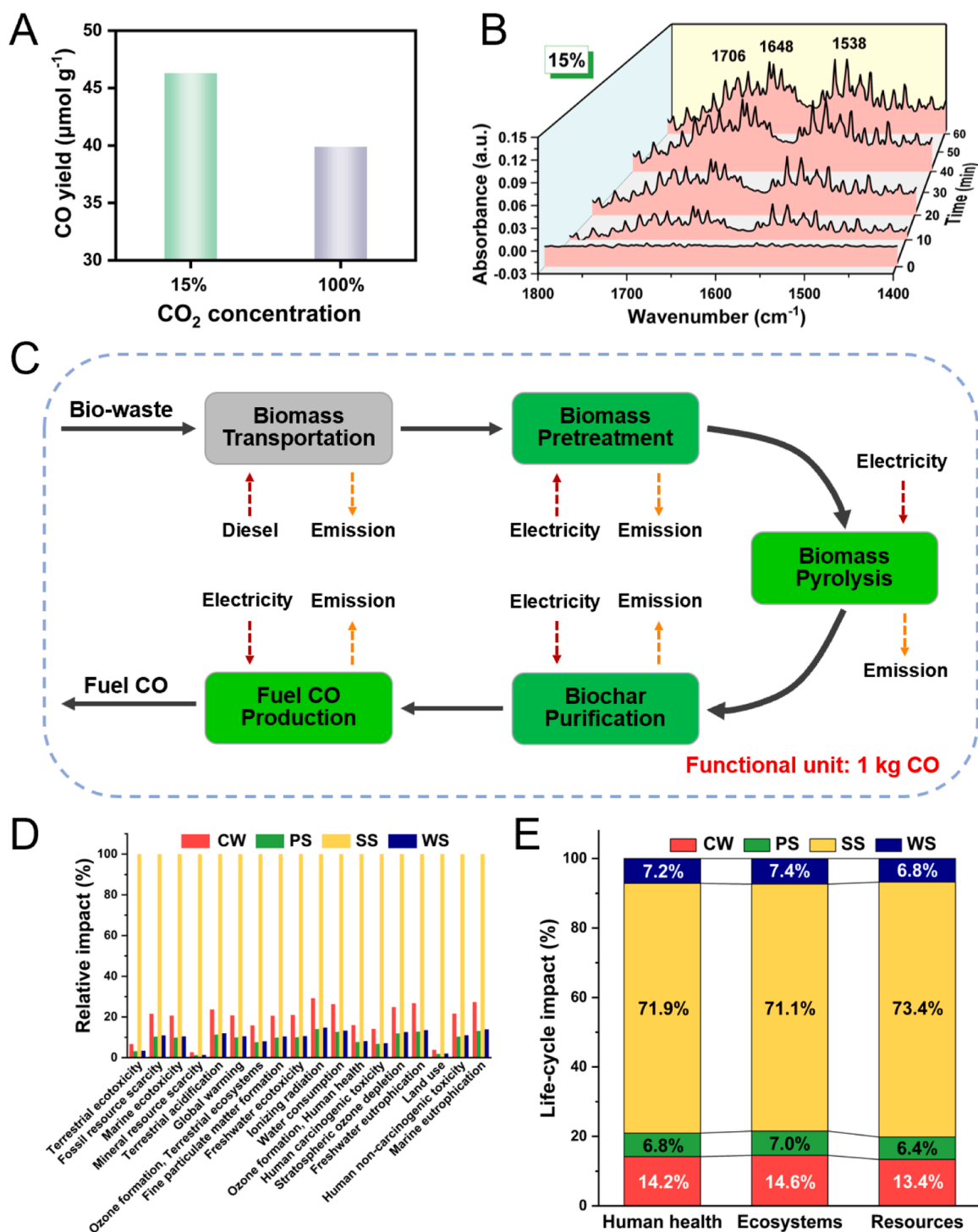


Fig. 5. (A) Production of CO on PS350 biochar for photocatalytic conversion of CO_2 of different concentrations. (B) In situ DRIFTS of adsorption of 15% CO_2/N_2 on PS350 in the presence of H_2O within 60 min at 30°C . (C) System boundary of life cycle assessment for production of fuel CO from solar conversion of CO_2 by biochar. Comparison of LCIA (D) characterization and (E) normalized aggregated results by ReCiPe 2016 Midpoint (H)/World (2010) H and ReCiPe 2016 Endpoint (H)/World (2010) H/A methods.

specific key oxygen-containing functional groups as well as interaction mechanism.

3.3. Practical application and life cycle assessment

Since environmental systems of pure CO₂ are barely existent in practice, 15% CO₂/N₂, as the typical CO₂ concentrations in flue gas, was selected to examine the application of biochar in solar conversion of CO₂. As shown in Figs. 5A and S19, the yield of CO increased under the condition of 15% CO₂/N₂ (46.3 μmol·g⁻¹), even higher than that under the pure CO₂ condition, indicating promising prospective of the biochar in waste gas resource utilization. In situ DRIFTS of adsorption in different reaction atmospheres of pure CO₂ and 15% CO₂/N₂ were carried out (Figs. 4A and 5B). The peak intensities of the key *COOH and HCO₃⁻ intermediates in the flue gas of 15% CO₂/N₂ were more intensive than that in the gas environment of pure CO₂, suggesting that the lower CO₂ concentration was beneficial for the adsorption and activation, resulting in the more effective conversion of CO₂ to fuel. These results confirm that waste biomass-derived biochar have promising applications in utilization CO₂ in the industrial flue gas under practical conditions.

In order to further evaluate the sustainability of waste biomass-derived biochar for CO₂ solar conversion, a life cycle assessment (LCA) was conducted to quantify the environmental impact and contribution of the process for CO fuel production from CO₂. Waste biomass-to-CO fuel (cradle-to-gate) and 1 kg of CO product were defined as the system boundary and functional unit in the analysis, respectively (Fig. 5C). The inventory of inputs and outputs for the whole product life cycle is summarized in Table S8, where the data were obtained from databases, literature, calculations, and experiments, etc. Next, the environmental impacts in the process of CO fuel production from CO₂ by different waste biomass-derived biochar (including 18 impact indicators, Table S9) were quantitatively analyzed based on the ReCiPe 2016 Midpoint (H)/World (2010) H methodology [3,61]. Based on 18 midpoint categories, the photoconversion of CO₂ on biochar from low-temperature pyrolysis of PS and WS biomass exhibited considerable environmental superiority, followed by CW, while SS showed the environmental unfriendliness (Fig. 5D). We normalized and aggregated the results of 22 impact categories calculated with the ReCiPe 2016 Endpoint (H)/World (2010) H method (Table S10) to three higher-level LCIA impact indicators of human health, ecosystems, and resources [3, 61]. According to the normalized aggregated results (Table S11 and Fig. 5E), the CO fuel production system from PS and WS showed lower environmental footprint than that from CM and SS. Taken together, the selection of waste biomass with more cellulose and lignin as precursors for biochar was more conducive to achieving efficient CO₂ conversion and environmental benefits.

4. Conclusion

Waste biomass-derived biochar were prepared from woody, herbaceous, chemical sludge, and livestock manure with different characteristics at relatively low pyrolysis temperatures. The biochar was applied in solar conversion of CO₂ to high-value CO fuel. The pine sawdust-derived biochar with rich carbonyl functional groups yielded the highest CO fuel with the aid of greater CO₂ adsorption capacity, in the absence of any sacrificial, metal agents, or heating. It performed even more excellent in 15% CO₂/N₂, a typical CO₂ concentration in the industrial flue gas. Furthermore, the life-cycle assessment revealed that the biochar derived from biomass with more cellulose and lignin exhibited higher CO₂ conversion and environmental benefits. This work provides a new breakthrough on the application of biomass waste-derived biochar in high efficiency solar conversion of CO₂ for sustainable energy and environment.

CRediT authorship contribution statement

Xueyang Zhang: Validation, Resources, Methodology. **Li Jin:** Validation, Methodology. **Xianli Yang:** Resources, Methodology. **Weixin Zou:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Xiaoqian Wei:** Writing – original draft, Validation, Software, Methodology, Investigation, Data curation. **Lin Dong:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Bin Gao:** Writing – review & editing, Supervision, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.apcatb.2024.123957.

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