Abstract

Biomass, as a renewable resource, plays a key role in the transition to sustainable, clean energy technologies, which is vital for achieving net-zero emissions. Pyrolysis and gasification can convert biomass into valuable biofuels, helping mitigate the climate change and improve energy security. Co-gasification of biomass with petroleum coke (petcoke), a by-product of oil refining, takes advantage of their complementary characteristics. This approach improves the reactivity of the blended fuel samples. The natural presence of alkali and alkaline earth metals in biomass acts as catalysts, enhancing the gasification process and promoting sustainable biofuel production. This synergistic interaction optimizes the conversion of biomass and petcoke and addresses environmental concerns by reducing waste, lowering sulphur emissions and contributing to a sustainable energy landscape.

Pyrolysis experiments on Bambusa *tulda* are conducted using a fixed-bed pyrolysis system and a thermogravimetric analyzer under nitrogen and carbon dioxide atmospheres. The study aimed to understand the thermal degradation behavior, focusing on biomass and char's physicochemical, structural, and elemental characteristics. Kinetic analysis is performed at heating rates of 10, 20, 30, and 40 K min^{-1} to determine the activation energy, pre-exponential factor, and kinetic model. Blending B.*tulda* with petroleum coke (petcoke) at various ratios provided insights into the synergistic effects on thermal behavior and reaction kinetics. The results showed significant weight loss during the second stage of pyrolysis, mainly due to the degradation of hemicelluloses, cellulose, and a small amount of lignin. Under the CO_2 atmosphere, the weight loss reached about 95 %, compared to 80 % under the N_2 atmosphere, indicating enhanced carbon consumption facilitated by CO_2. Iso-conversional methods revealed average activation energies of 160.05 kJ mol^{-1} for B. *tulda* in N_2 and 105.51 kJ mol^{-1} in CO_2 atmosphere. Blending with petcoke further reduced activation energy and improved thermal conversion, with values of 101.66 kJ mol^{-1}, 122.23 kJ mol^{-1}, and 129.30 kJ

mol^{-1} for Biomass 80% and Petcoke 20% (B80P20), Biomass 60% and Petcoke 40% (B60P40), and Biomass 40% and Petcoke 60% (B40P60) blends, respectively. The catalytic effects of alkali and alkaline earth metals in B. *tulda* contributed to these enhancements.

Criado's master plots validated the kinetic mechanisms by reaction model fitting to the thermal degradation process. The pre-exponential factors varied with the blending ratios, highlighting different reaction mechanisms at each thermal degradation stage. A strong linear relationship between activation energy and pre-exponential factors across conversion fractions confirmed the kinetic compensation effect. The biochar produced in a CO_2 atmosphere (BCC) exhibited larger and more developed pores than those generated in an N_2 atmosphere (BCN), which displayed a more porous and organized structure. The channel-like structure in BCC is attributed to the development of an aromatic framework. Additionally, the carbon content and calorific value of the char are significant, with BCC showing higher values at 85.16 % carbon content and a calorific value of 29.44 MJ kg^{-1}, compared to BCN, which had 81.23 % carbon content and a calorific value of 25.36 MJ kg^{-1}. These findings highlight the potential of Bambusa *tulda* char as a viable feedstock for gasification processes or as an alternative to conventional fossil fuels.

Single particle combustion of B. *tulda* blended with petcoke is conducted at varying ratios and particle sizes (20 mm, 25 mm, and 30 mm). The key parameters examined include combustion time, flame behavior, mass degradation, ignition mass flux, and ash composition. The results indicate that volatile combustion contributes to 70-80 % of total mass loss in all blends. However, when the petcoke content exceeds 40 wt %, overall mass conversion decreases to below 50 %, attributed to the low volatile content and high fixed carbon and density of petcoke. The ignition mass flux increases with higher petcoke content during volatile combustion but declines during char combustion due to the slower combustion rate caused by the high fixed carbon content of petcoke. A higher surface area-to-volume ratio also reduces combustion time, enhancing the coupling between heat and mass transfer and facilitating more efficient particle conversion. The study observed a synergistic effect of blending B. *tulda* with petcoke, significantly reducing the potassium content in ash from 50 wt% to 25-30 % and sulfur content by 40 %. This reduction minimizes ash deposition, corrosion, and slagging, resulting in cleaner emissions and better environmental performance.

The interaction between carbon-rich feedstock and catalysts is crucial for improving conversion efficiency, optimizing product gas composition, and ensuring process stability during gasification. This study focuses on using CO_2 as a gasification medium, contributing to CO_2 recycling and reducing emissions. Key operational parameters, such as catalyst, temperature, and pressure, are analysed for their impact on gasification. Bamboo and petroleum coke are utilized as feedstock, with potassium carbonate as the catalyst. The results indicate that biochar impregnated with a catalyst produces higher CO concentrations than unimpregnated biochar. A significant increase in CO production and char conversion is observed as the temperature increases from 1023 K to 1173 K under varying pressures. At 1173 K, ash residues melt, which affects char conversion. Furthermore, blending petroleum coke with catalyst-loaded bamboo char demonstrates a synergistic effect of alkali metals on the CO_2 gasification process. Increasing the proportion of bamboo char in the blend enhances the CO fraction and char conversion. These findings are significant for CO_2 recycling and optimizing petroleum coke-blended fuels in gasification processes.

This research establishes B. *tulda* as a versatile and renewable biomass feedstock with applications in combustion and gasification. It's blending with industrial byproducts like petcoke offers a pathway to cleaner and sustainable energy solutions. The findings highlights the potential of *B. tulda* and petcoke blending to contribute to global clean energy transitions by providing scalable alternatives to fossil fuels, while also supporting circular economy goals through the innovative utilization of industrial byproducts