

Thermochemical Valorization of Sugarcane Bagasse: Thermo-Kinetic Analysis and Pyrolysis Product Sustainability Assessment

Abstract

Sugarcane bagasse (SCB) is a lignocellulosic agricultural residue generated during the mechanical crushing and juice extraction of sugarcane in sugar mills. Large quantities of SCB are produced annually, and its effective utilization offers significant opportunities for sustainable waste management, renewable energy production, and greenhouse gas emission reduction. Owing to its high volatile matter, low ash content, and abundant availability, SCB has emerged as a promising low-cost renewable feedstock for thermochemical conversion and the production of value-added bioenergy products. This study comprehensively investigates the pyrolysis behavior and biochar characteristics derived from SCB, focusing on kinetic, thermodynamic, and physicochemical analyses. Thermogravimetric analysis (TGA) was conducted at heating rates of 10, 20, 30, and 40 °C/min over a temperature range of 25–900 °C to evaluate the thermal decomposition of SCB. The thermal decomposition process was divided into three distinct stages, corresponding to hemicellulose, cellulose, and lignin degradation. Iso-conversional methods Flynn–Wall–Ozawa (FWO), Kissinger–Akahira–Sunose (KAS), Starink, and Friedman were employed to calculate activation energies, yielding average values of 168.89, 162.52, 174.70, and 323.46 kJ/mol, respectively. The Coats–Redfern model was applied to identify the reaction mechanism and determine pre-exponential factors. Thermodynamic parameters confirmed SCB's viability as a pyrolysis feedstock. Slow pyrolysis of SCB was carried out at three temperatures (400, 500, and 600 °C), with a 1-hour holding time, a nitrogen flow rate of 100 cm³/min, and two particle sizes (0.40 mm and 1 mm). The resulting six biochar samples were analyzed for yield, structure, surface morphology, and agronomic properties. Characterization techniques included proximate and CHNS elemental analysis, X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), Raman spectroscopy, and Brunauer–Emmett–Teller (BET) surface area analysis. Biochar yield decreased with increasing temperature, ranging from 36.85% at 400 °C (BC1, 1 mm) to 25.14% at 600 °C, owing to enhanced devolatilization and secondary cracking reactions. These biochar yields indicate efficient thermochemical conversion of SCB and confirm its suitability as a promising feedstock for producing value-added carbonaceous materials for environmental and energy applications. High-temperature pyrolysis (600 °C) resulted in biochar with higher pH (up to 10.4), enhanced stability,

aromaticity, and heating value (HHV), indicating its potential for long-term carbon sequestration and energy applications. In contrast, low-temperature biochars (400 °C) exhibited higher volatile content, diverse functional groups, better energy recovery, and improved suitability as soil amendments. BET surface area significantly increased with both temperature and reduced particle size from 12 to 337 m²/g (1 mm) and 29 to 555 m²/g (0.40 mm), respectively. However, the cation exchange capacity (CEC) decreased with increasing pyrolysis temperature. This study demonstrates that pyrolysis temperature and particle size play a decisive role in governing the thermokinetic behavior, product distribution, and physicochemical properties of SCB-derived biochar. By integrating kinetic, thermodynamic, and comprehensive material characterization, the work provides a systematic framework for optimizing SCB pyrolysis to produce application-specific biochar, thereby advancing the sustainable thermochemical valorization of agricultural residues.

Keywords: *Biomass, Sugarcane bagasse, Pyrolysis, Thermogravimetric Analysis (TGA), Kinetics, Activation energy; Iso-conventional methods, Pyrolysis Temperature, Biochar, bio-oil*