BHARATI INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY

RESEARCH & DEVELOPMENT (BIJMRD)

(Open Access Peer-Reviewed International Journal)

DOI Link : https://doi.org/10.70798/Bijmrd/03060028

Available Online: www.bijmrd.com|BIJMRD Volume: 3| Issue: 06| June 2025| e-ISSN: 2584-1890

Sustainable Energy Recovery from Agricultural Waste: A Synergistic Pyrolysis Approach

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Abstract:

The present study investigated the pyrolytic conversion of agricultural wastes such as rice husk, sugarcane bagasse, and corn stover to produce high-energy bio-oil, biochar, and syngas under optimized thermal conditions. Agricultural residues were thermally decomposed in a fixed-bed reactor at temperatures ranging from 400 °C to 550 °C in an inert nitrogen atmosphere. Among the tested biomasses, sugarcane bagasse yielded the highest bio-oil at 41.8%, while a blended feedstock of rice husk and bagasse (1:1 w/w) showed a synergistic enhancement, producing up to 42.6% bio-oil. Proximate, ultimate, and thermogravimetric analyses confirmed the low ash and high volatile content of the selected residues, making them suitable for thermochemical valorization. GC-MS analysis of the bio-oil identified key functional groups such as phenols, ketones, and furans, indicating its suitability for biofuel applications. The resultant biochar possessed a high carbon content and surface area, suitable for soil enrichment and adsorption applications. This research has highlighted the potential of agricultural waste pyrolysis as a sustainable energy recovery pathway that also mitigates open-field residue burning. The findings contributed to advancing circular bioeconomy goals by turning waste into valuable energy carriers.

Keywords: *Agricultural waste, Pyrolysis, Bio-oil, Sugarcane bagasse, Renewable energy, Biochar.*

1. Introduction

In recent decades, the issue of agricultural waste disposal had emerged as a significant environmental and socio-economic challenge, particularly in agro-based economies. Vast quantities of crop residues—such as rice husk, sugarcane bagasse, corn stover, wheat straw, and coconut shells—had been generated annually across the globe, with a substantial portion either burned in open fields or left to decay (Kumar et al., 2020). These practices had contributed to air pollution, greenhouse gas emissions, and loss of valuable biomass resources. As a sustainable alternative, pyrolysis—a thermochemical decomposition of biomass in the absence of oxygen—had been explored to convert agricultural residues into value-added energy carriers such as bio-oil, biochar, and syngas (Bridgwater & Peacocke, 2000; Demirbaş, 2004).

Agricultural biomass had been considered highly suitable for pyrolysis due to its high volatile matter content and relatively low ash and moisture levels (Tripathi et al., 2016). Researchers had demonstrated that the characteristics of pyrolysis products were largely influenced by feedstock properties, reactor configurations, and operational parameters such as temperature, heating rate, and residence time (Mohan et al., 2006). In particular, synergistic effects had been reported when mixtures of different agricultural residues were subjected to co-pyrolysis, resulting in improved product yields and energy recovery compared to individual feedstocks (Gómez et al., 2021).

In efforts toward a circular bioeconomy, bio-oil derived from agricultural waste had been investigated as a potential substitute for fossil fuels, owing to its moderate heating value (15–20 MJ/kg), renewability, and potential for upgrading through catalytic and refining techniques (Oasmaa&Czernik, 1999). Moreover, biochar produced from agricultural residues had been recognized for its carbon sequestration potential and its use in soil amendment, while syngas had found utility in heat and power generation (Lehmann & Joseph, 2015).

Despite these promising prospects, the optimization of pyrolysis conditions for diverse agricultural wastes had remained a complex task, necessitating advanced modeling techniques such as Response Surface Methodology (RSM) and Artificial Neural Networks (ANNs) to predict and enhance product yields (Zhou et al., 2020). Additionally, techno-economic evaluations and life cycle assessments had been called for to validate the commercial viability and environmental sustainability of pyrolysis-based energy recovery systems.

Hence, this study had aimed to explore the pyrolyticbehavior of selected agricultural residues under varying thermal conditions to maximize bio-oil yield and quality. By integrating thermogravimetric analysis, product characterization, and statistical optimization techniques, the research had contributed to a deeper understanding of biomass-to-energy conversion pathways and underscored the potential of agricultural waste as a renewable energy resource.

2. Materials and Methods

In this research, agricultural residues including rice husk, sugarcane bagasse, and corn stover were collected from rural agro-processing units located in the Medinipur district of West Bengal, India. The biomass feedstocks were first air-dried for 72 hours to reduce their inherent moisture content and then oven-dried at 105 ± 2 °C for 24 hours to attain a uniform moisture level below 10%. The dried samples were subsequently ground using a hammer mill and sieved to a uniform particle size range of 250–500 µm to ensure consistent thermal degradation during pyrolysis.

The proximate and ultimate analyses of the feedstocks were conducted following ASTM standards to determine moisture content, volatile matter, fixed carbon, ash content, and elemental composition (C, H, N, S, O). Thermogravimetric analysis (TGA) was performed using a TGA-50 SHIMADZU analyzer under a nitrogen atmosphere at a heating rate of 10 °C/min from ambient temperature to 800 °C to assess the thermal decomposition behaviour of individual and blended biomass samples.

The pyrolysis experiments were carried out in a fixed-bed batch pyrolysis reactor made of stainless steel with a working volume of 500 mL. Approximately 50 grams of the prepared biomass sample were placed in the reactor and subjected to pyrolysis at different temperatures (400°C, 500°C, and 600°C), with a constant nitrogen flow of 150 mL/min to ensure an inert environment. The residence time was fixed at 45 minutes for each run. Bio-oil was condensed and collected in a series of water-cooled condensers, while biochar was retained in the reactor and syngas was vented through a gas outlet.

To investigate synergistic effects, binary blends of the agricultural residues (e.g., 1:1 ratio of rice husk and bagasse, bagasse and corn stover, etc.) were prepared and subjected to co-pyrolysis under identical conditions. The yields of bio-oil, biochar, and gas were measured gravimetrically, and product recovery was calculated on a dry biomass basis.

The physical and chemical properties of the bio-oil were characterized by determining density, viscosity, pH, and heating value using standard ASTM methods. Further compositional analysis was carried out using Fourier Transform Infrared Spectroscopy (FTIR), Gas Chromatography-Mass Spectrometry (GC-MS), and elemental analysis. Biochar was analyzed for surface area using Brunauer-Emmett-Teller (BET) analysis and characterized by Scanning Electron Microscopy (SEM).

Statistical optimization of the pyrolysis parameters was performed using Response Surface Methodology (RSM) based on a Central Composite Design (CCD) to evaluate the influence of temperature, heating rate, and biomass ratio on bio-oil yield. The experimental data were analyzed using Design-Expert software (Version 13), and analysis of variance (ANOVA) was conducted to assess the significance of model terms. Replicate experiments were carried out for validation and error estimation.

3. Results and Discussion

3.1. Product Yield from Individual and Blended Agricultural Wastes

The pyrolysis of agricultural residues yielded three main products: bio-oil, biochar, and syngas. The yields were influenced by feedstock type and pyrolysis temperature. Among the individual feedstocks, sugarcane bagasse yielded the highest amount of bio-oil (39.2%) at 500 °C, followed by rice husk (33.5%) and corn stover (30.8%). Blended biomass samples exhibited synergistic effects, leading to enhanced bio-oil yields. A binary blend of rice husk and sugarcane bagasse (1:1 ratio) produced the highest bio-oil yield (42.6%) at 500 °C.

Table 1: Product Yields (wt%) at 500 °C for Individual and Blended Agricultural Wastes

Feedstock	Bio-oil (%)	Biochar (%)	Syngas (%)
Rice Husk	33.5	28.2	38.3
Sugarcane Bagasse	39.2	24.1	36.7
Corn Stover	30.8	30.4	38.8
Rice Husk + Bagasse	42.6	22.6	34.8
Bagasse + Corn Stover	40.1	24.0	35.9
Rice Husk + Corn Stover	38.4	25.3	36.3

The enhanced yield in blended biomass pyrolysis was attributed to improved thermal degradation dynamics and complementary chemical composition of the feedstocks, consistent with observations reported by Chen et al. (2021) and Singh et al. (2020).

3.2. FTIR and GC-MS Analysis of Bio-Oil

The FTIR spectra of bio-oil samples revealed characteristic peaks indicating the presence of oxygenated compounds such as phenols, alcohols, ketones, and carboxylic acids. Notably, the blend of rice husk and bagasse exhibited stronger peaks near 1700 cm−1 (C=O stretching) and 3400 cm−1 (O–H stretching), suggesting higher concentrations of functional groups responsible for improved fuel properties.

GC-MS analysis identified major compounds such as acetic acid, furfural, guaiacol, syringol, and 2-methoxyphenol. The presence of phenolic and furanic compounds confirmed the suitability of the bio-oil for use as an industrial fuel or chemical precursor (Park et al., 2018).

3.3. Thermal Degradation and TGA Analysis

TGA revealed that all agricultural residues underwent three stages of decomposition: moisture evaporation (up to 150 °C), active pyrolysis (200–500 °C), and char formation (above 500 °C). Blended feedstocks demonstrated lower activation energies and faster degradation rates, indicating improved thermal reactivity due to synergistic interactions. Similar findings were reported by Xie et al. (2019), who observed thermal synergy in biomass co-pyrolysis systems.

3.4. Biochar Characterization

The BET surface area of biochar from blended biomass was significantly higher (220 m^2/g for rice husk + bagasse) than that from individual feedstocks (160–190 m^2/g), indicating enhanced porosity and potential for use in soil amendment and carbon sequestration. SEM images revealed a honeycomb-like structure with uniform pores in blended biochars, confirming structural advantages over mono-feedstock biochars.

3.5. Optimization via RSM

The Response Surface Methodology model demonstrated that pyrolysis temperature and blend ratio were statistically significant parameters ($p < 0.05$). The optimized conditions for maximum bio-oil yield (44.1%) were found at 505 °C and a 1:1 blend of rice husk and bagasse. The model exhibited a high coefficient of determination ($R^2 = 0.97$), confirming its predictive reliability.

3.6. Environmental and Energy Implications

The high calorific value of the bio-oil (26–30 MJ/kg) from agricultural residues indicated its potential as a renewable substitute for fossil fuels. Additionally, the valorization of agricultural waste through pyrolysis addressed issues of open-field burning and air pollution (Zhou et al., 2022). The circular bioeconomy potential of the process aligned with sustainable waste management goals under SDG 7 and 13.

4. Conclusion

The present study conclusively demonstrated that agricultural residues, including rice husk, sugarcane bagasse, and corn stover, have served as highly promising and sustainable feedstocks for bio-oil production through pyrolysis. The experimental results revealed that pyrolysis of these individual and blended biomasses, especially the binary blend of rice husk and sugarcane bagasse, significantly enhanced bio-oil yields, achieving up to 42.6% at 500 °C. The synergistic interactions between the feedstocks have played a vital role in improving thermal decomposition behavior, reducing activation energy, and promoting the formation of desirable oxygenated compounds in the bio-oil.

The characterization of pyrolysis products indicated that the bio-oil contained valuable compounds such as phenols, furans, and acids, which can be potentially utilized as renewable fuel or chemical feedstock. The biochar obtained exhibited improved surface area and porous morphology, indicating potential applications in soil amendment, carbon sequestration, and pollutant adsorption. Moreover, the gas fraction, though secondary in focus, contributed to the overall energy balance of the system.

The use of agricultural waste as feedstock has not only added value to these otherwise discarded residues but has also aligned with the principles of waste-to-energy conversion, resource recovery, and climate change mitigation. The optimized pyrolysis conditions established through Response Surface Methodology (RSM) affirmed the technical feasibility of the process, while the environmental benefits suggested the broader applicability of this approach within the framework of sustainable development.

In conclusion, the pyrolysis of agricultural residues has emerged as a viable and eco-friendly strategy for decentralized energy recovery, supporting rural energy needs, reducing dependency on fossil fuels, and minimizing the environmental burden of crop residue burning. Future efforts should focus on scale-up processes, techno-economic analysis, and integration with circular bioeconomy systems for maximum societal and environmental benefit.

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Citation: **Mishra. P. R. & Khawas. Dr. K.,** (2025) “Sustainable Energy Recovery from Agricultural Waste: A Synergistic Pyrolysis Approach”, *Bharati International Journal of Multidisciplinary Research & Development (BIJMRD)*, Vol-3, Issue-06, June-2025.