

Extended Abstract

(For Ph.D. Open Seminar)

Thermochemical Conversion of Agricultural-Biomass to Engineered Biochar and Composites for Environmental Applications

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Degree for which submitted: Doctor of Philosophy

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Energy and environment are two interlinked pillars for sustainable growth of a nation and emphasize waste utilization, renewable energy, low emissions, circular economy, etc. . In this context, it becomes important for an agrarian and developing economy like India to use agricultural biomass in a scientific and sustainable way. Agriculture is the most important part of India's economy and society. It provides livelihood opportunity for more than half of the people. India is one of the top producers of agricultural goods in the world since it has one of the greatest areas of land that can be farmed. Agricultural activity leaves behind a lot of biomass waste, which is one of the most common and underused renewable resources. This agro biomass waste generated amounts in millions of tonnes annually during harvesting, processing, and post-harvest operations. The improper management of this biomass—such as open-field burning, land dumping, or uncontrolled decomposition—leads to serious environmental challenges, such as air pollution, greenhouse gas (GHG) emissions, loss of soil's nutrients, and loss of potentially valuable carbon resources. In this context, the conversion of unutilized agricultural biomass waste into value-added materials such as biochar, activated carbon and biochar-based composite materials has gained significant attention due to their multifunctional applications in energy storage, environmental remediation, soil amendment, carbon sequestration, and sustainable material development.

Pyrolysis is an established thermochemical conversion process of conversion of agricultural biomass waste into valuable materials such as biochar, bio-oil, and synthesis gas. It involves heating of biomass in the absence of oxygen at higher temperatures, typically in the range of 300°C to 800°C. The key objective of this research is to transform different types of agricultural biomass waste into biochar using controlled pyrolysis or co-pyrolysis and to evaluate its physiochemical characteristics and functional properties and explore its application potentials. The further work was carried out to develop activated carbon and biochar-based composite materials to enhance performance in targeted applications such as adsorption of dye from contaminated water, CO₂ adsorption, etc. By optimizing parameters such as temperature, residence time, heating rate etc. for the pyrolysis process and composite preparation method, the research seeks to improve properties such as yield, surface reactivity, porosity, etc.

Beyond laboratory-scale findings, this work has a broader implication for sustainable waste management, climate action, and the growth of a circular bioeconomy. Processing of agricultural residues for preparation of biochar, activated carbon and biochar based composite materials not only creates value-added products but also helps in minimizing adverse effect of unscientific and unsustainable way of its handling. More notably, biochar provides a pathway

for long-term carbon sequestration by locking biomass-derived carbon in stable forms for years.

This research aims to connect the domains of material science, environmental engineering, and sustainability by offering a comprehensive understanding of biomass pyrolysis, optimization of biochar properties, and development of advanced composite materials. The findings have the potential to support cleaner production practices, encourage the circular use of agricultural residues, and provide scientific insights that can strengthen policies focused on reducing biomass waste and promoting renewable, eco-friendly materials.

The work in the thesis has been organized in the following eight chapters:

Chapter 1: Introduction

This talks about current energy and environment-related challenges by highlighting dependency on fossil fuel and greenhouse gas emission associated with its burning. It also discusses the subject of energy security. It furthered the discussion about renewable energy sources and the potential of agricultural biomass as a key renewable energy resource. It also presents the classification, key properties, and availability of biomass resources across the country. The chapter further describes the chemical composition of biomass—which typically consists of cellulose, hemicellulose, and lignin—and discusses the major technological methods used to convert biomass into value-added products, highlighting biomass pyrolysis, a thermochemical method for biomass utilization.

Chapter 2: Literature Survey

This chapter gives the detailed classification of biomass and presents a biomass atlas of India highlighting the total and surplus biomass generation of each state. It discusses in detail biomass pyrolysis, its product, and factors affecting biomass pyrolysis. It further discusses the previous works done by various researchers related to biomass pyrolysis and co-pyrolysis.

Chapter 3: Materials and methodology

This chapter discusses the instrument and procedure adopted for biomass processing, biochar preparation, and materials characterization. It discusses in detail the pyrolysis setup used for this study. The major characterization techniques discussed here are CHNS analyzer, calorific value determination using bomb calorimetry, thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy (FT-IR), field-emission scanning electron microscope (FE-

SEM), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, UV-Vis (ultraviolet-visible spectroscopy), and the Brunauer–Emmett–Teller (BET) surface area analyzer.

Chapter 4: Pyrolysis of Rice Straw and Sugarcane bagasse for production of biochar

This chapter presents experimental work on biomass pyrolysis of rice straw, sugarcane bagasse, and their mixture at different temperatures ranging from 300 to 700°C. The biomass feedstocks used were in the form of both pellets and powder. The various physicochemical properties of the produced biochar were evaluated at different temperatures. The pellet and powder forms of biochar were also compared for their properties.

Chapter 5: Pyrolysis of Rice straw and Mustard-Oil Residue for sustainable applications

This chapter discusses the pyrolysis of rice straw and mustard-oil residue, as well as their co-pyrolysis, to determine the optimal mixture ratio for achieving the best results. Combining de-oiled cake with less dense rice straw powder helped in quality pellet formation, having significant strength and durability. The pyrolysis was carried different temperature (300-600°C) and the different properties were evaluated to show its potential application for biochar gasification and energy application.

Chapter 6: Green synthesis of biochar-graphene oxide composite for enhanced dye adsorption

In this chapter rice straw biochar was prepared following the earlier discussed method. Then graphene oxide was synthesized in the laboratory using the well-established modified Hummer's method. Using mechanical stirring and ultrasonication, the GO and biochar were mixed properly. The mixture was further put under hydrothermal conditions to ensure the proper bonding of GO over biochar surfaces. The materials thus prepared were named as RS-GO-0.1 and RS-GO-1 depending on the biochar and GO compositions. These composites were characterized and tested for methylene blue dye adsorption. The result shows superior adsorption have adsorption efficiency of 99.29% for a 20-ppm methylene blue solution.

Chapter 7: Development of Nitrogen (N)-doped Activated Carbon (AC) using Mango Kernel Biomass for CO₂ Entrapment Applications

This chapter discuss the preparation of biochar from mango kernal biomass and its activation using potassium hydroxide (KOH). The activated carbon was further treated with urea (NH₂CONH₂) to introduce nitrogen functionalities over the surfaces and improve its CO₂

capture potential. Its structural and surface analyses confirmed the successful activation and presence of additional functional groups that support entrapment capacity. N-doped activated carbon was further combined with a suitable additive to improve the stability of entrapped CO₂ bubbles. This combined system was evaluated to understand its ability to retain CO₂ under controlled conditions. The overall aim of this chapter was to demonstrate how biomass-derived carbon materials can be engineered for efficient CO₂ entrapment.

Chapter 8: Conclusion and future scope

This chapter summarizes the work discussed above in all the chapters and outlines the future scope of this research work.

List of Publications

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1. **Pandey, H.**, Pandey, A., Sinha, A.S.K. et al. Conversion of rice straw and sugarcane bagasse waste to biochar through pyrolysis: influence of feedstock and process conditions. J Mater Cycles Waste Manag (2025). <https://doi.org/10.1007/s10163-025-02329-x>
 2. **Pandey, H.**, Pandey, A., & Agrahari, G. K. (2025). Pyrolysis of rice-straw and mustard-oil residue blend: evaluation of biochar properties for its sustainable use. Biofuels, 1–9. <https://doi.org/10.1080/17597269.2025.2484075>
 3. Green Synthesis of Biochar–Graphene Oxide Composite via Hydrothermal Route for Superior Adsorption of Dye from Aqueous Phase. (Submitted)
 4. Synthesis of surfactant modified N-doped activated carbon using mango kernel for sustainable utilization in CO₂ adsorption. (under preparation).

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