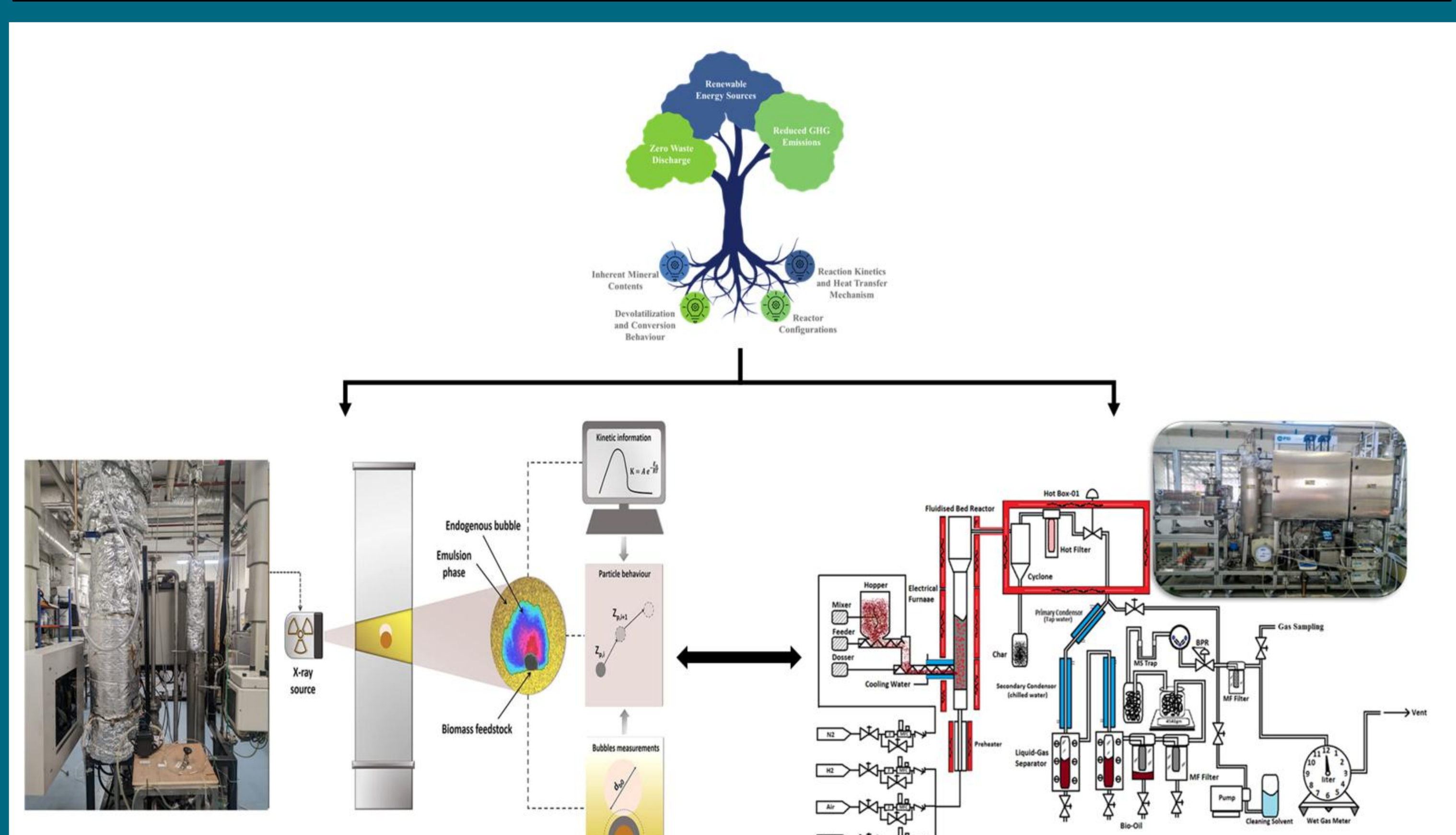
From Waste to Wings: Closed-Loop Drop-In Fuel Production via an Integrated Thermo-Catalytic Process

Abhisek Sahoo

Priority Topic Area: **Responsible Production, Innovation and Industry**

1 – Waste: A Burden or A Treasure?

Waste, often seen as an environmental burden, holds immense potential as a resource. With sustainability in focus, waste valorization tackles both ecological and energy challenges. This research examines converting biomass and waste into drop-in biofuels via an integrated thermo-catalytic process. This circular approach transforms waste into a treasure for future energy solutions. By 2050, global waste could hit 3.4 billion tonnes yearly, straining economies and ecosystems. Yet, waste biomass—from agricultural scraps to municipal refuse—offers a carbon-neutral feedstock. Unlike landfilling or incineration, closed-loop technologies create high-value fuels, cutting pollution and fossil fuel reliance, decarbonizing sectors like aviation and shipping.



Reactor with X-Ray Image Technique

Dual Stage Closed-loop Reactor Setup

2 – Each step counts for a sustainable future

The two-step fluidized bed reactor is optimized for agricultural residues, with fluidization velocity tuned via X-ray imaging to resolve biomass heterogeneity. Step 1: Fast pyrolysis (500°C, N_2) converts biomass into char and vapours. Step 2: Vapours undergo hydrogenation in a catalytic chamber using activated biochar-derived catalysts (CO_2-activated, 800°C), selectively deoxygenating bio-oil into drop-in fuels. Off-gases (H_2/CO-rich syngas) are recycled to power the reactor, ensuring self-sufficiency.

Key Innovations:

- X-ray-guided reactor design for feedstock-specific fluid dynamics.
- Activated carbon supports transition metal carbide catalysts.
- Closed-loop energy integration and syngas recirculation.

This system achieves zero toxic discharge while maximizing resource efficiency.

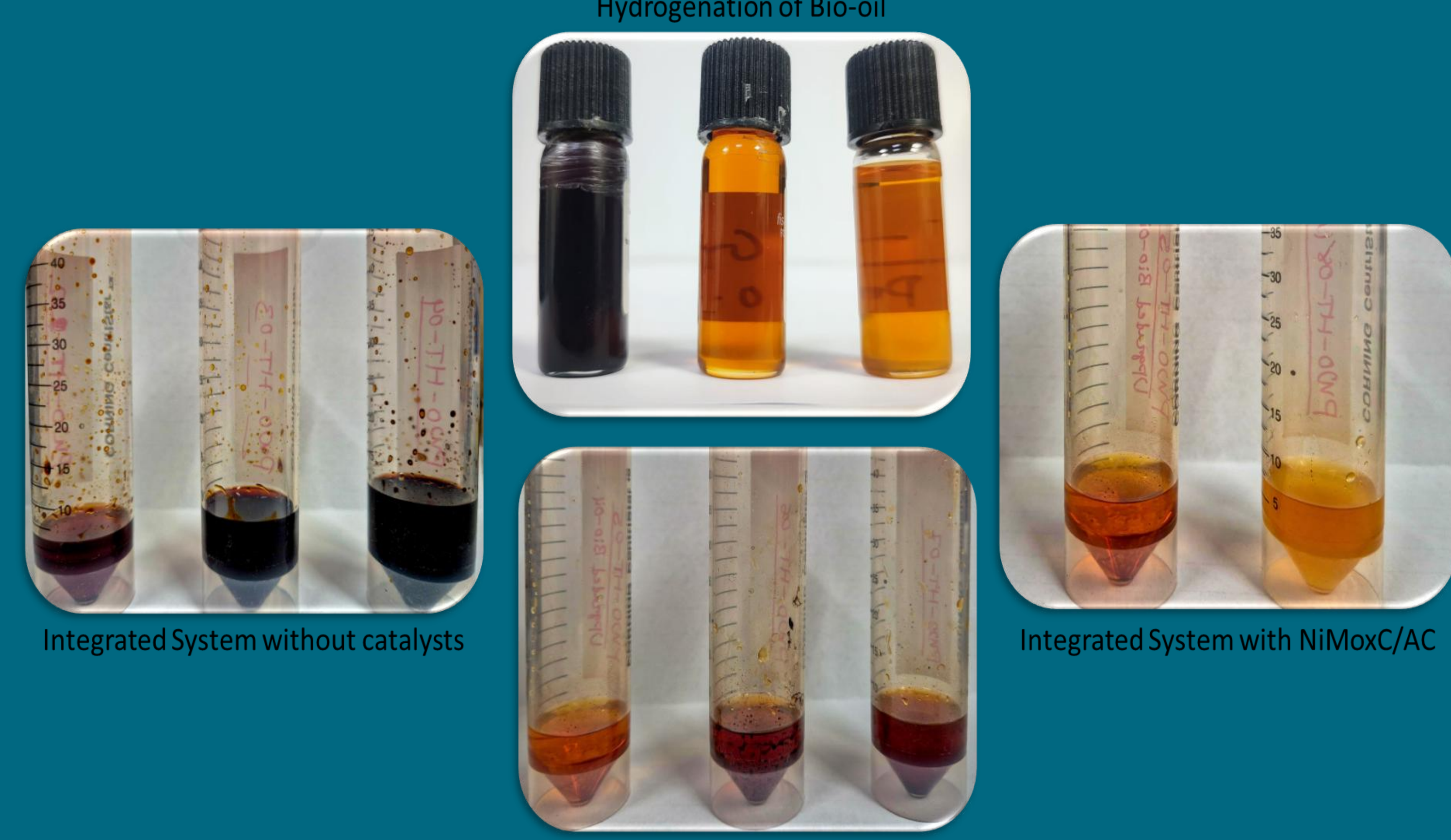
3 – Outputs/Results/findings

Our study successfully processed various agricultural residue biomass through an integrated thermo-catalytic process, yielding gasoline-range fuels with less than 10 wt.% oxygen content. This significant oxygen reduction enhances fuel stability and compatibility with existing fuel infrastructure, making it a promising drop-in fuel alternative.

We performed biomass inherent analysis inside the reactor using X-ray imaging techniques to gain deeper insights into the conversion mechanisms. These advanced imaging methods allowed us to observe structural transformations, devolatilization behaviour, and reaction dynamics in real time, providing critical data for process optimization. The results revealed distinct shrinkage patterns, porosity evolution, and thermal degradation stages, offering valuable information for improving reaction efficiency.

Overall, our findings validate the feasibility of a closed-loop, waste-to-fuel approach, proving its potential for large-scale adoption. By integrating real-time imaging with advanced catalytic upgrading, we establish a scientifically driven and industrially scalable pathway toward sustainable fuel production, reducing reliance on fossil fuels while ensuring cleaner energy solutions for the future.

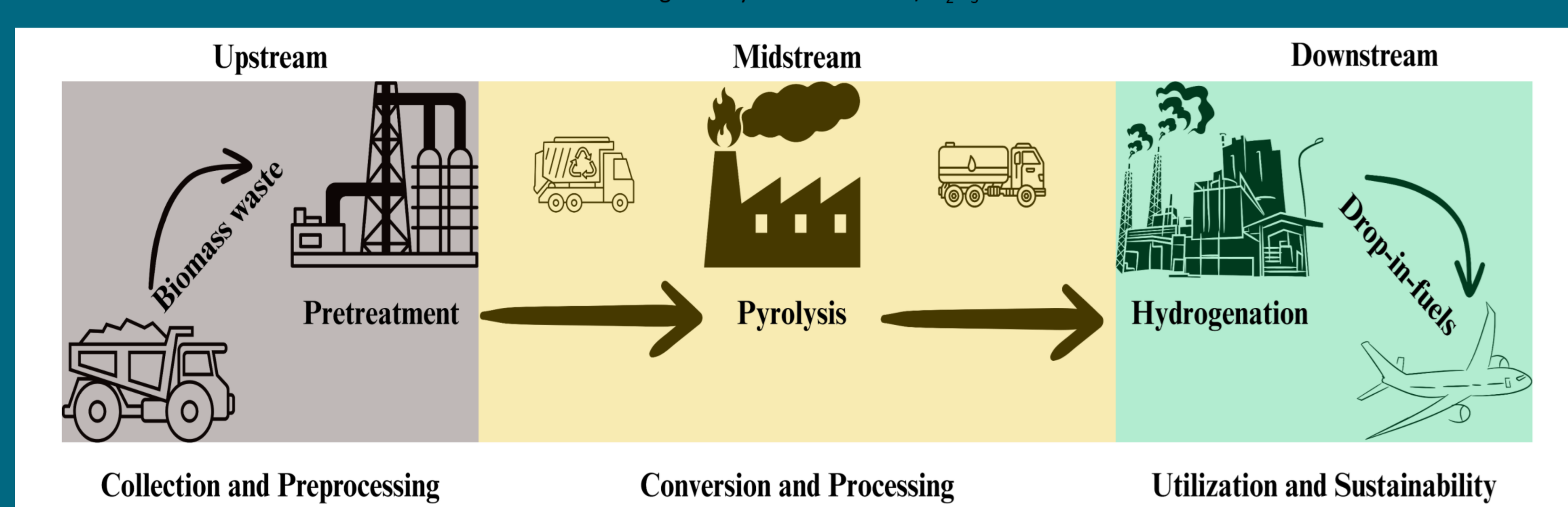
Hydrogenation of Bio-oil



Integrated System without catalysts

Integrated System with NiMoxC/AC

Integrated system with NiMo/Al_2O_3



4 – Sustainability is our responsibility

Our integrated process converts waste into valuable resources, reducing landfill dependency and minimizing harmful emissions. It ensures a zero-waste, zero-emission system by generating clean energy and high-value drop-in fuels while recovering essential by-products. This innovation strengthens the circular economy, decreases reliance on fossil fuels, and fosters sustainability. It also aligns with key global sustainability goals 7, 9, &12, addressing critical environmental and energy challenges. Beyond energy benefits, this process improves air quality, reduces toxic pollutants, and mitigates health risks linked to waste mismanagement, ultimately enhancing public well-being and contributing to a cleaner, more resilient, and sustainable future for all.

5 – Next steps

Optimizing catalyst formulations to further enhance fuel quality and yield while minimizing oxygen content. We aim to scale up the process for industrial applications and integrate AI-driven process modelling. Additionally, exploring co-processing petroleum refinery by-products with biomass can further advance the circular economy and sustainable fuel production.

IChemE YOUNG ENGINEERS AWARDS for Innovation and Sustainability

Acknowledgements

Chemical Reaction Engineering (CRE) Lab, IIT Delhi
BioEnergy Technology Research (BETR) Lab, UCL London

COMMONWEALTH SCHOLARSHIPS

IChemE