Valorisation of Oil Palm Biomass Waste for Bio-Oil and Hydrogen Production Using Red Mud-Based Catalysts

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Abstract
Indonesia's oil palm industry, a major contributor to global palm oil supply, generates a huge amount of biomass waste, including trunks, fronds, and empty fruit bunches (EFB), especially during routine replanting and milling processes. The accumulation of these residues, while partially utilized for composting and mulching, represents an underutilized energy resource. This research investigates the valorisation of such biomass waste via catalytic pyrolysis to produce bio-oil and hydrogen, using red mud (RM), a waste by-product from bauxite refining, as a heterogeneous catalyst.

Catalyst preparation involved washing, drying, and calcining RM at 800°C to improve surface area and pore structure, confirmed by BET and XRD analyses. The resulting catalyst showed increased specific surface area and pore volume, with XRD and XRF revealing dominant Al_2O_3 and Fe_2O_3 phases. Catalytic pyrolysis was conducted at varying temperatures (400°C–600°C), catalyst concentrations (5%–15% w/w), and under nitrogen flow. The products were characterized via GC-MS and FTIR.

Results demonstrated that the presence of RM catalyst notably increased the yield of volatile compounds and hydrogen-rich gases. Specifically, pyrolysis yields reached 18–40 wt.% for bio-oil and 23–37 wt.% for hydrogen, depending on feedstock type and operational parameters. The use of RM facilitated enhanced cracking of heavier compounds, yielding more condensable liquids and gaseous products while reducing bio-char formation.

Among the biomass types studied, oil palm trunks showed the highest gas yields, attributable to their lower lignin and higher cellulose content. Meanwhile, EFB produced the highest liquid yield due to optimal cellulose and hemicellulose composition. Fronds exhibited intermediate behaviour but benefited significantly from elevated temperatures, especially due to their higher lignin content, which decomposes over a broader thermal range.

GC-MS analysis of the bio-oil showed dominant oxygenated compounds including acetic acid, furans, phenols, and esters. While the oxygen-rich nature lowers calorific value, it confirms the efficient depolymerization of biomass components. RM also promoted deoxygenation reactions, essential for improving bio-oil quality. The gas phase contained hydrogen, carbon monoxide, carbon dioxide, and methane, with trunks contributing the highest H_2 yield.

Temperature elevation improved pyrolysis performance by increasing gas and liquid yields, though diminishing returns were observed beyond 500°C for EFB and trunks. Additionally, higher RM concentrations promoted further cracking of tar and biochar, increasing bio-oil production up to an optimal loading. However, excessive catalyst dosage beyond 15% may lead to secondary reactions unfavourable for liquid product selectivity.

In conclusion, the study successfully demonstrates a synergistic waste-to-energy route, converting oil palm biomass into valuable fuels using red mud catalyst. This integrated approach supports Indonesia's renewable energy goals and contributes to global efforts in sustainable waste management, resource recovery, and green hydrogen production.

Keywords: biomass waste, bio-oil, hydrogen, oil palm, red mud