

Biochar as a Catalyst in Biorefineries: A Sustainable Recovery of Waste Materials

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The concept of biorefinery has gained significant attention in recent years to tackle the challenges of climate change and resource depletion faced by the world [1], [2]. Biorefineries have the potential to transform naturally abundant biomass into an array of valuable products, including biofuels, biochemicals, and biomaterials [1], [3].

Biochar is a carbon-rich material typically produced from biomass through pyrolysis. Owing to its unique characteristics, such as large surface area, tunable porous structure, mechanical and thermal stability, and acid/alkali resistance, it is recognized as a promising catalyst for various biorefinery processes [4]–[6]. Moreover, biochar produced from biomass can reduce the carbon footprint and help to achieve sustainability of the entire biorefinery process [7].

In pyrolysis, the biomass is subjected to high temperatures (300–900 °C) in an oxygen-free atmosphere to produce solid, liquid and gaseous fractions [4], [8]. The porous and highly stable solid fraction obtained is called biochar [9], [10]. Traditionally, biochar is used as a soil conditioner to improve soil fertility and carbon sequestration. In recent years, its applications have extended to various industrial and environmental fields, including biorefinery processes

[11], [12].

Biochar based catalysts are widely used in several refining processes including hydrothermal liquefaction of biomass [4], [7], isomerization and dehydration [12], catalytic pyrolysis and gasification [4], [7], transesterification of vegetable oils for biodiesel production [4], [12], biogas production [12], hydrogenation [12], catalytic cracking [4], catalytic reforming [4], and upgradation of biomass [12].

To improve the performance, the biochar is subjected to physical and/or chemical modification depending on the intended applications [4]. Steam and CO₂ are typically used to activate the biochar produced by pyrolysis. Steam and CO₂ activation results in an increase in surface area and porosity of the biochar. It is reported that the surface area increases up to 200 times after gas activation [12]. Additionally, CO₂ activation introduces surface defects and oxygen-containing functional groups. In chemical modification, NaOH, KOH, sulfuric acid, phosphoric acid, chlorosulfonic acid and ZnCl₂ are commonly used for biochar activation. The loading ratio of the activating agent, impregnation time, activation temperature and activation temperature influence the activation efficiency [4], [12]. Depending on the activating agent

used, surface functional groups such as -OH, -SO₃H, -COOH, etc., are added to the biochar. Introducing these functional groups particularly favors acid catalyst reactions, such as esterification and hydrolysis. It has been reported that ZnCl₂ results in swelling of biochar during activation and, hence results in the expansion of pores.

Alternatively, loading of biochar with metals (Ag, Cu, Fe, Ni, Sn, Tn, Zn, Zr), functional materials (carbon nanotubes, graphene, graphene oxide, and zero valent iron) and few heteroatoms (B, N, P and S) can improve the catalytic performance of the biochar [4]. Metal impregnation increases the active sites (for ex. Lewis acid sites) on biochar [12]. Introducing Lewis acidity and Bronsted acidity improves the catalytic efficiency of the biochar in heterogeneous reactions, such as transesterification reactions and hence activated biochar is popular in biodiesel production. In biomass valorization, Bronsted to Lewis acid ratio and hydrophobicity play significant role in controlling the reaction rate kinetics [12]. These properties of biochar are tailored during their production. Thus, biochar has the potential to replace the commonly used solid acid catalysts [13]. Also, for certain metal catalysts biochar acts as a stable support.

Another important operation in biorefinery is biomass upgradation. Biochar can be used as a catalyst for biomass valorization by facilitating processes like deoxygenation and decarboxylation [4], [7]. Owing to the carbonaceous nature of biochar, it acts as a reducing agent and enables the removal of oxygen-containing functional groups from biomass to enhance the quality and value of the generated products.

Thus, due to the versatile roles of biochar in biorefinery applications, it is emerging as a valuable catalyst in the transition towards more sustainable and environmentally friendly resource recovery. As the biorefinery industry evolves continuously, the innovative use of biochar catalysts offers a promising avenue for the creation of wealth from waste, reducing carbon emissions, and promoting circular and sustainable bioeconomy.

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