How do biochar properties shape its catalytic performance?

Biochar (BC) properties play a key role in determining its catalytic activity, particularly in the removal of organic micropollutants, with pesticides representing one of the most relevant groups. Some of the most important factors include specific surface area, porosity, oxygen-containing functional groups, surface charge, elemental composition, and preparation conditions. These characteristics govern how BC interacts with micropollutants and oxidants, and ultimately define whether the process will rely more on adsorption or catalytic degradation.

The specific surface area and porous structure are fundamental parameters that determine the efficiency of BC, as they directly influence its adsorption capacity and the distribution of catalytically active sites [1]. A higher surface area provides a greater number of accessible active sites, while a well-developed pore network facilitates the transport of micropollutant molecules and oxidants to those sites. At the same time, oxygen-containing functional groups supply chemically reactive sites that enable a variety of interactions with contaminants, including hydrogen bonding, π–π interactions, and electrostatic attraction, thereby further enhancing catalytic activity [2,3]. The presence of these groups is particularly important in advanced oxidation processes (AOPs), where they can act as initiation points for oxidant activation and the generation of reactive oxygen species (ROS), which are primarily responsible for the degradation of organic micropollutants.

The choice of feedstock plays a significant role. Primary materials such as corn straw, sawdust, or pomelo peel generally yield BC with greater surface area and pore volume compared to secondary feedstocks such as sludge, food waste, or manure, where high ash content may block pores and reduce adsorption efficiency [4,5]. Moreover, the inorganic components present in secondary feedstocks can alter the surface chemistry of BC, potentially reducing its stability and catalytic performance.

Pyrolysis conditions are equally critical. Elevated temperatures increase specific surface area and pore volume by removing volatile matter and expanding graphitic layers [6,7], although excessively high temperatures may reduce efficiency by decreasing the abundance of oxygenated functional groups and causing partial pore collapse [8]. In contrast, lower pyrolysis temperatures preserve a greater number of surface functionalities, while moderate heating rates and longer residence times promote the development of well-defined porous structures [9]. This interplay between structure and chemistry needs to be carefully controlled to achieve optimal catalytic performance.

Surface charge is another key parameter shaping BC-micropollutant interactions, and its behavior depends on solution pH relative to the point of zero charge (pH_{pzc}). When the pH is below the pH_{pzc}, the BC surface becomes positively charged, which favors the adsorption of negatively charged micropollutants and oxidants through electrostatic attraction [10]. Under such conditions, the probability of effective collisions between micropollutants and ROS is enhanced, while the

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deprotonation of surface groups can lead to the generation of surface-bound persistent free radicals that further improve catalytic processes.

Altogether, these insights show that BC is not a static material but a highly tunable platform. By carefully selecting feedstocks, controlling pyrolysis conditions, and applying targeted modification strategies, it is possible to tailor BC properties toward specific environmental applications. Understanding these relationships is therefore essential to maximize catalytic activity and ensure the efficient removal of organic micropollutants from water and other environmental matrices.

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