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SPOTLIGHT

An Overview on the Catalytic and Photocatalytic Applications of Biochar Compiled by

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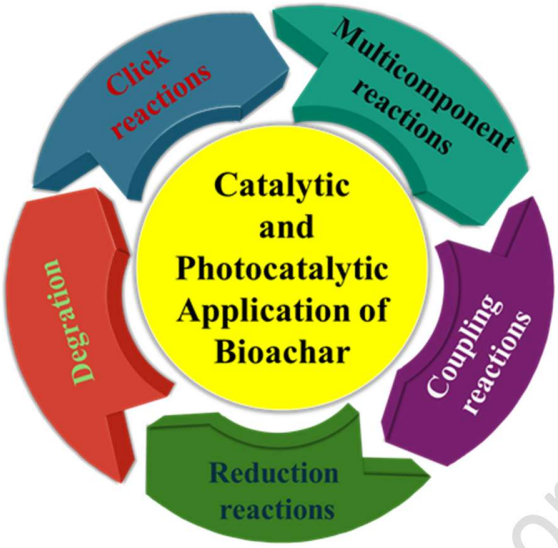
Introduction

Biochar nanoparticles represent a cutting-edge carbon substrate utilized in catalysts, derived from the pyrolysis of biomass and renewable resources under conditions of restricted oxygen and high pressure, resulting in a porous material. Conversely, carbon possesses characteristics such as varied porous structures, affordability, easy accessibility, excellent recyclability, and compatibility with a range of synthesis techniques, rendering carbon an ideal base material for catalysts [1-2]. Biochar has a wide range of applications, such as catalytic and photocatalytic, agriculture, carbon absorption, etc., which have attracted much attention today. As mentioned, biochar is a solid rich in the element carbon that can be produced from the pyrolysis of agro-food

industrial waste. As a result, it can be converted into biochar as a biological adsorbent. On the other hand, it is also widely used for soil and water treatment. For catalytic synthesis of biochar, the post-synthesis modification method can be used because the biochar surface is rich in functional groups that give it diverse catalytic and photocatalytic synthesis power. For example, by using acids, alkalis, oxidizing agents, and metal ion modification, biochars with different properties can be synthesized [3-4]. Due to the high porosity of biochar and the various functional groups present on its surface, including carboxyl groups, hydroxyl (OH-) groups, and amine groups, biochar can be easily used for immobilization and dispersion of nanoparticles, enhancing the development of various catalysts [5-6]. In addition, the physical and chemical properties of biochar can be modified with acid or base treatment. On the other hand, biochar is a highly porous, carbon-rich material, which could be a suitable alternative to other solid carbon catalysts, some of which have known disadvantages such as high cost and environmental hazards.

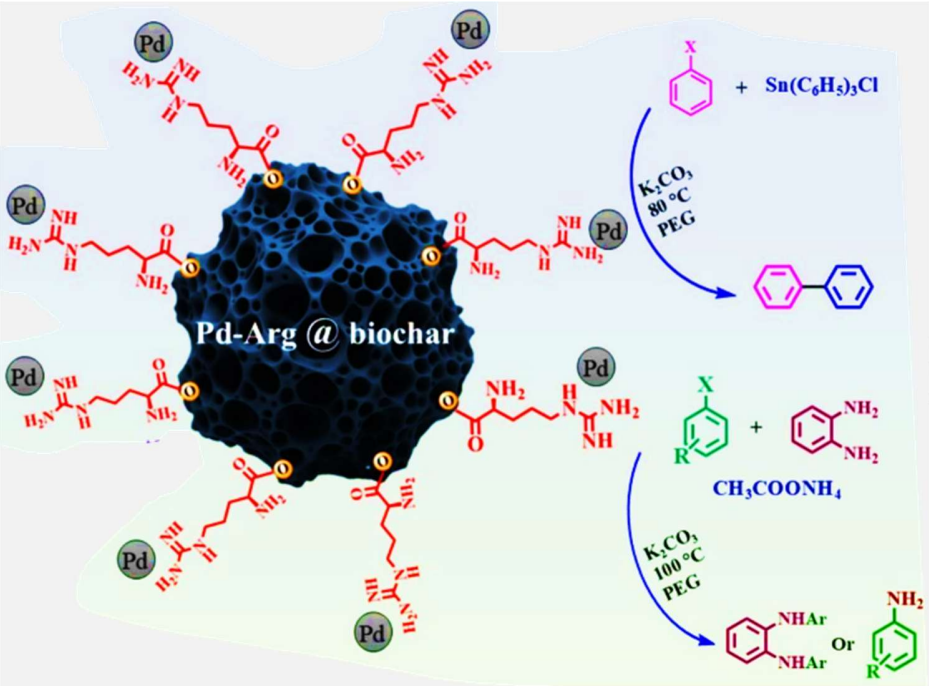
Therefore, biochar is an excellent choice for low-cost and cost-effective catalytic applications with high efficiency. In this spotlight, attempts are made to highlight several catalytic and photocatalytic applications of biochars in various reactions, including oxidation-reduction, multicomponent couplings, etc. (**Scheme 1**).



Scheme 1. Schematic diagram showing the various catalytic and photocatalytic applications of biochar.

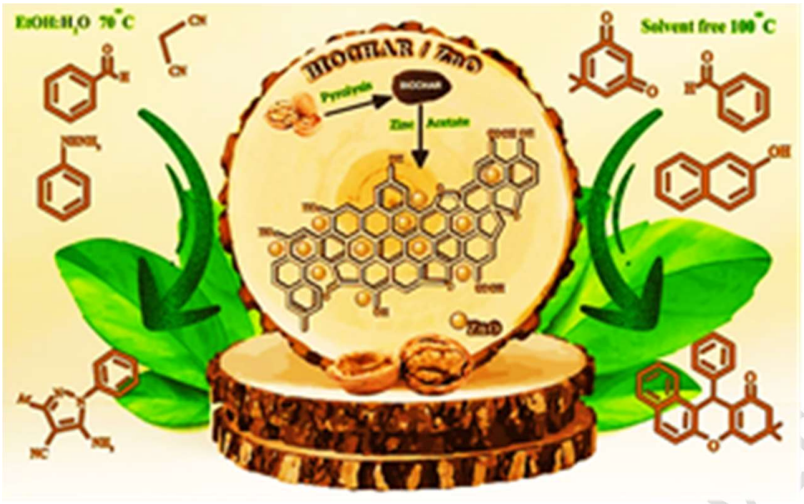
Abstract:

(A) Biochar is a carbon-rich substrate produced by thermochemical decomposition of biomass at high temperature. In general, functional groups provide great stability and diversity to the porous structure of biochar; for example, functional groups containing oxygen provide a better and more efficient catalytic substrate. In 2025, Hajjami and co-workers synthesized a modified arginine-biochar catalyst used to immobilize palladium nanoparticles. This synthesized biocatalyst, which had high recyclability, was used in C-C and C-N coupling reactions for the synthesis of biphenyls and arylamines (Scheme 2) [7].



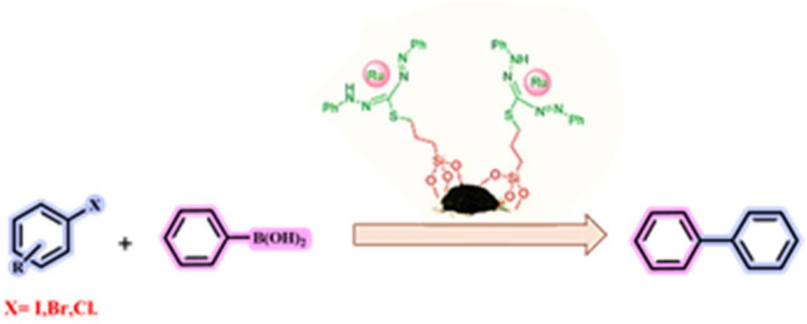
Scheme 2. Hajjami and co-workers synthesized a modified arginine-biochar catalyst used to immobilize palladium nanoparticles.

(B) Nowadays, biochar/zinc oxide composite nanoparticles have been widely used as an environmentally friendly biocatalyst. The combination of zinc oxide nanoparticles and biochar substrate helps to increase the surface area and improve the active sites for catalytic reactions. For this purpose, Hajjami et al. designed and synthesized a catalyst based on biochar/zinc oxide composite nanoparticles in 2025 and investigated its catalytic performance in the synthesis of tetrahydrobenzo[a]xanthen-11-one derivatives under solvent-free conditions and also for the synthesis of 5-aminopyrazole-4-carbonitrile derivatives in a 1:2 ethanol-water mixture. According to the results obtained, this biocatalyst has high efficiency, reusability, and easy separation, which has a great impact on chemical stability (Scheme 2) [8].



Scheme 2. synthesized a catalyst based on biochar/zinc oxide composite nanoparticles and investigated its catalytic performance in the synthesis of tetrahydrobenzo[a]xanthen-11-one derivatives.

(C) The use of recyclable catalysts is very important in chemistry. Biochars are among the catalysts that can be recycled and reused easily. Hajjami et al. synthesized and introduced a catalyst called Ru-dithizone@biochar-Ni MNPs in 2022. To synthesize the catalyst, magnetic biochar nanoparticles (biochar-Ni MNPs) were modified by the dithizone ligand, and then ruthenium metal was complexed with the ligand used (Ru-dithizone@biochar-Ni MNPs). The developed catalyst served as a functional, selective, and recyclable nanocatalyst, boasting simple separation properties in the Suzuki carbon-carbon coupling reaction conducted in an aqueous setting (Scheme 3) [9].

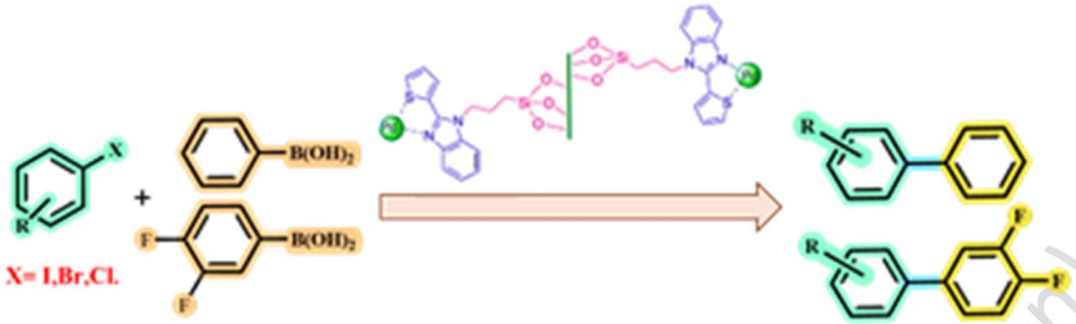


Scheme 3. Synthesized a catalyst called Ru-dithizone@biochar-Ni and used it in the Suzuki carbon-carbon coupling reaction.

(D) In 2024, Hajjami and colleagues synthesized biomass for the production of biochar nanoparticles using olive pomace. The biochar surface was functionalized with the ligand L-histidine, and then copper acetate was added to prepare Cu-L-histidine biochar as the final catalyst for the chemical and homoselective synthesis of amide and aniline derivatives. A notable feature of this catalyst is its reusability, which maintains significant efficiency even after multiple uses in reactions (Scheme 4) [10].

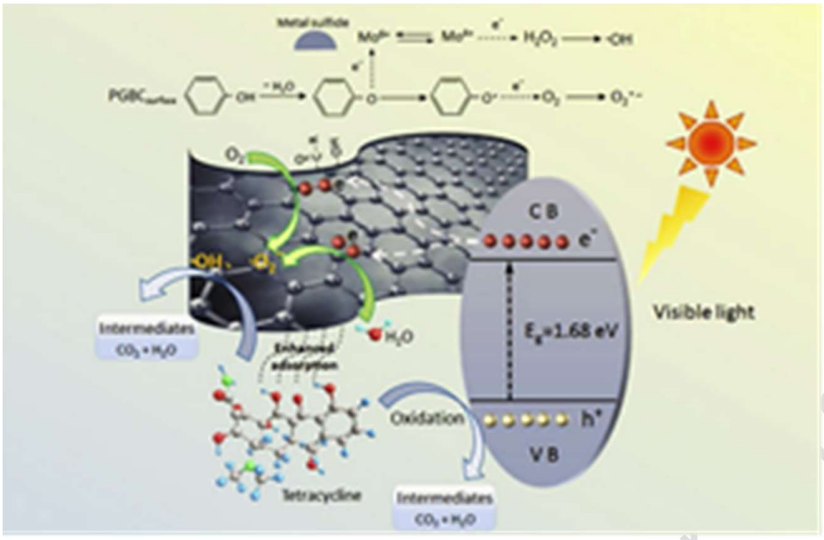
Scheme 4. Synthesized Cu-L-histidine biochar and used in a reduction reaction.

(E) In 2019, Hajjami et al. synthesized a biochar-based catalyst by modifying the surface of biochar nanoparticles (BNPs) with 3-chloropropyltrimethoxysilane and immobilizing 2-(thiophen-2-yl)-1H-benzo[d]imidazole on its surface. Then, palladium nanoparticles were deposited on the surface of the modified BNPs and studied as recyclable biocatalysts in carbon-carbon coupling reactions such as Suzuki-Miura and Heck-Mizuruki cross-coupling reactions (Scheme 4) [11].



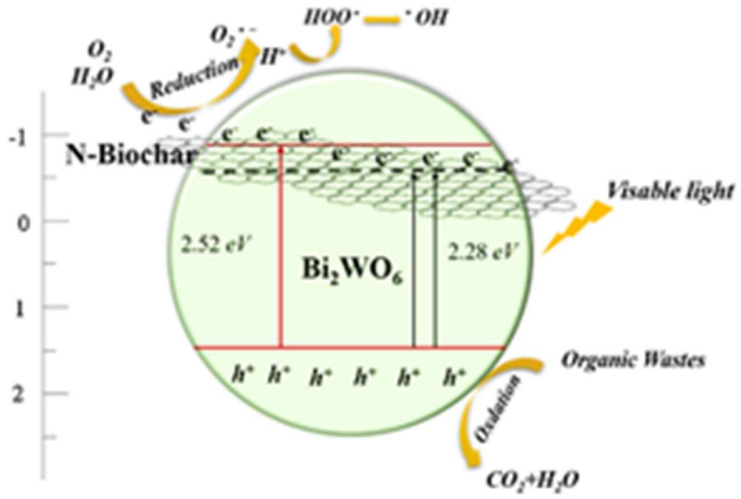
Scheme 4. Synthesized BNPs biochar and used in Suzuki-Miura and Heck-Mizuruki cross-coupling reactions.

(F) Zeng et al. synthesized a porous graphitic carbon biochar composite in 2019 and used it for the removal of tetracycline hydrochloride from water, especially river water. Porous graphitic biochar (PGBC) containing g-MoS2 nanosheets, due to its high specific surface area and optimized band gap, led to accelerated charge transfer and efficient separation of light-generated carriers. This photocatalyst had high photocatalytic ability due to the presence of g-MoS2 sheets and thus showed very high efficiency for the removal of tetracycline hydrochloride (TC). By confirming the proposed mechanism, it can be said that the adsorption was mainly due to electrostatic interaction, hydrogen bonding, and pore filling, with hole (h+) and hydroxyl radical (OH.) as the dominant active species, which caused the degradation of TC (Scheme 5) [12].



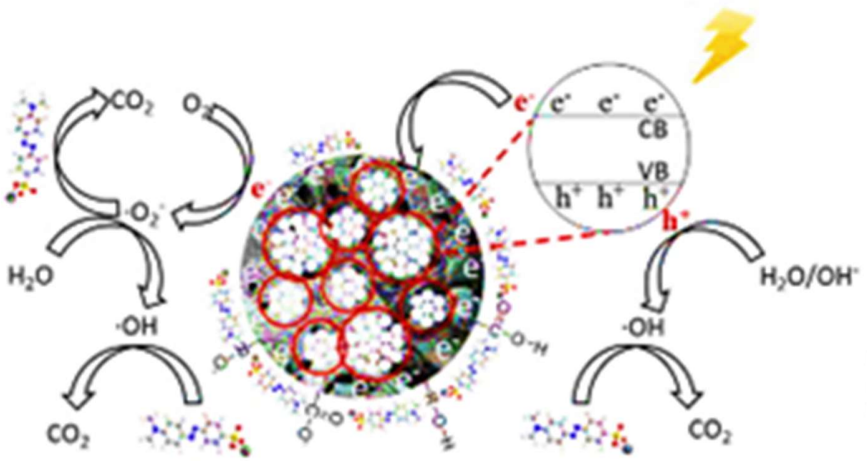
Scheme 5. Synthesized a porous graphitic carbon biochar composite and used it for the removal of tetracycline hydrochloride from water.

(G) In another study, Paz-Ferreiro et al. developed, synthesized, and documented N-biochar-Bi2WO6 (BW/N-B) composites for the removal of rhodamine-B and the reduction of Cr(VI) in water in 2020. To create the desired catalyst, biochar treated with urea and modified biochar exhibiting high conductivity and a 2D planar structure were produced. The incorporation of N-biochar resulted in the band gaps of the prepared composites being smaller than those of Bi2WO6, which could promote the transfer of electron-hole pairs generated by the photocatalytic activity of BW/B-N when exposed to visible light, thereby enhancing photocatalytic performance. The photocatalytic activity of the synthesized composite in the decomposition of 10 mg/L rhodamine B (RhB) and the reduction of Cr(VI) under visible light irradiation showed excellent results with high efficiency (Scheme 6) [13].



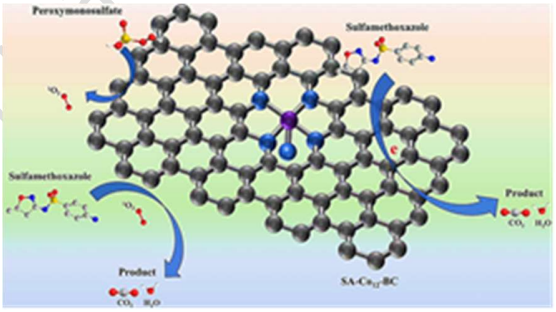
Scheme 6. synthesized a N-biochar-Bi_2WO_6 (BW/N-B) composite for the removal of rhodamine-B and the reduction of Cr(VI) in water.

(H) Biochar can be used for the degradation of organic dyes. In 2019, Yuan et al. developed a range of TiO2/biochar composite catalysts for degrading methyl orange, utilizing biochar sourced from the pyrolysis of walnut shells. Among the synthesized catalysts, CT0.1/1, CT0.2/2, and CT0.5/1 showed superior catalytic performance compared to pure TiO2. The CT0.2/1 catalyst exhibited the highest catalytic activity, achieving a decolorization efficiency of 96.88%, attributed to the synergistic effect of biochar and TiO2. Furthermore, after being recycled five times, the CT0.2/1 catalyst maintained relatively high activity for methyl orange degradation, demonstrating only a minimal decline in decolorization efficiency, which indicates that the reduction in catalytic activity was negligible (Scheme 7) [14].



Scheme 7. Synthesized a TiO_2/biochar composite catalysts for degrading methyl orange.

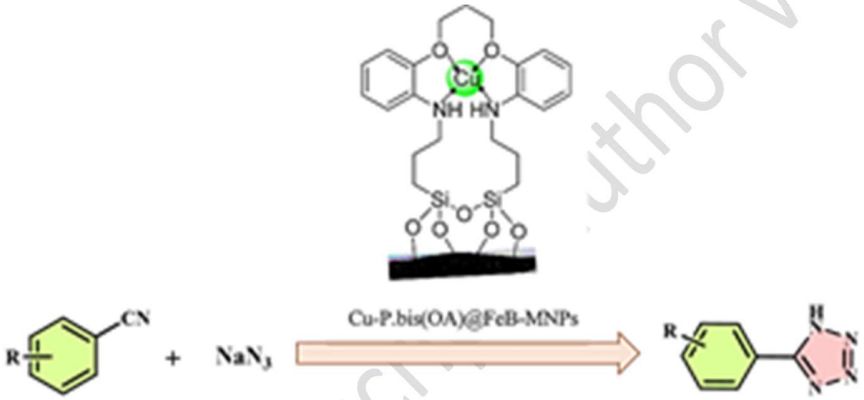
(I) Huang et al. (2025) utilized coffee ground waste biomass as a carbon-rich material to create the SA-Co12-BC/PMS catalyst for the breakdown of organic pollutants (AOPs), specifically for the elimination of sulfamethoxazole (SMX). The primary mechanisms for the degradation of SMX involve singlet oxygen (1O2) and an electron transfer pathway. Based on the reactions conducted with the synthesized catalyst, the SA-Co12-BC can sustain the removal rate of SMX at over 94% for 10 hours during continuous flow tests (Scheme 8) [15].



Scheme 8. synthesized a SA-Co12-BC/PMS catalyst for the breakdown of organic pollutants (AOPs) like sulfamethoxazole (SMX).

(J) In 2024, Tahmasbi and co-workers synthesized biochar nanoparticles (B-NPs) via pyrolysis of poultry manure. The synthesized biochar nanoparticles were magnetized using Fe(0)

nanoparticles. As a result, they modified the surface of the biochar magnetic nanoparticles (FeB-MNPs) using (3-chloropropyl)trimethoxysilane (3Cl-PTMS). Finally, they immobilized a polydentate copper complex of 2,2'-(propane-1,3-diylbis(oxy))dianiline (P.bis(OA)) onto the surface of the modified FeB-MNPs. The resulting nanocatalyst, which has high performance and recyclability, was used to synthesize 5-substituted-1H-tetrazole compounds via [3 + 2] cycloaddition of sodium azide (NaN3) and organonitriles in polyethylene glycol 400 (PEG-400), which is a green solvent (Scheme 9) [16].



Scheme 9. Synthesized a FeB-MNPs modified catalyst for the [3 + 2] cycloaddition reaction.

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