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Sewage Sludge-Derived Biochar for Micropollutant Removal: A Brief Overview with Emphasis on European Water Policy †

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Abstract: This work provides a brief overview of the application of Sewage Sludge-Derived Biochar (SSBC) for the removal of micropollutants from aqueous solutions and wastewater. A particular emphasis is placed on the adsorption efficiency of SSBC regarding the Priority Substances defined under the scope of the EU Water Framework Directive.

Keywords: Sewage Sludge; biochar; adsorption; micropollutants; Water Framework Directive

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1. Introduction

Micropollutants (MPs) are organic or inorganic substances that occur in the aquatic environment at low concentrations (ng to µg). The discharge of MPs into natural water bodies is not yet regulated by the European Union (EU) [1]. However, under the scope of the Directive 2000/60/EC, also known as the Water Framework Directive (WFD), 45 priority substances (PSs) that pose a risk to the aquatic environment have been defined to date.

Since effluents of wastewater treatment plants (WWTPs) are a major source of micropollutants in natural water bodies [2], the expansion of existing WWTPs by advanced micropollutant removal stages could improve the status of European natural waters. However, only a few techniques for the removal of MPs are in operation in European WWTPs, and mainly in Switzerland and Germany [3]. In these techniques, adsorption on activated carbon (AC) is the most frequently used process [4–6]. To reduce the cost of MP removal by adsorption, the development of new economic adsorbents is essential [7]. Recently, sewage sludge-derived biochar (SSBC) has been identified as a promising alternative to AC with respect to the circular economy [8].

This work briefly reviews the application of SSBC for the removal of micropollutants from aqueous solutions with an emphasis on the PSs defined under the scope of the WFD. Finally, the limitations of this research and future perspectives for micropollutants' removal from wastewater by SSBC are highlighted.

2. An Overview about the Removal of PSs by SSBC

This section aims to provide an overview of the state of the art regarding the application of SSBC for the removal of the 45 PSs defined under the WFD from aqueous solutions. A comprehensive number of studies ($n > 2$) were conducted on all metallic PSs:

- Cadmium;
- Lead;
- Mercury;
- Nickel and its compounds.

Several batch experiments using aqueous single-ion solutions proved the suitability of SSBC for the adsorptive removal of metallic PSs. The observed removal rates at the adsorption equilibrium varied in a wide range between <10% to ~100%, depending mainly on the SSBC dosages, initial metal concentrations, and the pH of the solution [9–12]. For Cadmium and lead removal, SSBC has shown better adsorption performances than commercial ACs tested as a reference [13–16]. When competitive metal ions were present in aqueous solutions, the adsorption efficiencies of SSBC decreased compared to single-ion solutions, with varying impacts for the respective ions. In these competitive ion studies, the adsorption performances of SSBC for metals followed this trend: Hg > Pb > Cd > Ni [16–19].

For the following organic PSs, a limited number of studies (n < 2) regarding their removal by SSBC have been carried out:

- Anthracene;
- Atrazine;
- Benzene;
- Nonylphenols;
- Octylphenols;
- Trifluralin;
- Perfluorooctane sulfonic acid and its derivates (PFOS).

The application of SSBC for the adsorptive removal of *anthracene*, *nonylphenols*, *octylphenols,* and other stormwater pollutants from aqueous solutions has been investigated in one study. In batch adsorption and kinetic tests, SSBC showed similar adsorption efficiencies for anthracene, nonylphenols, and octylphenols to two commercial ACs [20].

One study has been carried out on the application of SSBC for *atrazine* removal from a model solution and real wastewater spiked with various xenobiotics. At high adsorbent dosages, a full elimination of atrazine from the model solution was obtained for SSBC and two reference ACs. At lower dosages, the atrazine elimination rates of the SSBC dropped, whereas the removal rates of the commercial ACs remained at 100% [21].

In sorption experiments for the removal of *benzene* from aqueous solutions, SSBC was a weaker adsorbent than commercial ACs [22].

SSBC can be used as an adsorbent and as a redox catalyst for *trifluralin* removal from aqueous solutions. When SSBC was simultaneously used as an adsorbent and a catalyst for the degradation of trifluralin in the presence of a thiol reactant, the removal performance of SSBC increased significantly compared to its single use as an adsorbent [23].

Based on adsorption experiments, SSBC made from biosolids was evaluated as an excellent low-cost adsorbent for removing *PFOS* from aqueous solutions [24]. Accordingly, thermochemically activated SSBC exhibited a similar PFOS adsorption capacity to commercial ACs in another study [25].

For most of the PSs, no studies regarding SSBC's application in aqueous solutions are available. This concerns the following substances:

- Alachlor;
- Atrazine;
- Brominated diphenylethers (PBDE);
- Chloroalkanes ($C_{10–13}$);
- Chlorfenvinphos;
- Chlorpyrifos;
- 1,2-dichloroethane;
- Dichloromethane;
- Di(2-ethylhexyl)phthalate (DEHP);
- Diuron;
- Endosulfan;
- Fluoranthene;
- Hexachlorobenzene;
- Hexachlorobutadiene;

- Hexachlorocyclohexane;
- Isoproturon;
- Pentachlorobenzene;
- Pentachlorophenol;
- Polyaromatic hydrocarbons (PAH);
- Simazine;
- Tributyltin compounds;
- Trichlorobenzenes;
- Trichloromethane (chloroform);
- Trifluralin;
- Dicofol;
- Quinoxyfen;
- Dioxins and dioxin-like compounds;
- Aclonifen;
- Bifenox;
- Cybutryne;
- Cypermethrin;
- Dichlorvos;
- Hexabromocyclododecanes (HBCDD);
- Heptachlor and heptachlor epoxide;
- Terbutryn.

3. Conclusions

SSBC has great potential as a low-cost adsorbent for the removal of micropollutants from wastewater, especially for dissolved metals. However, the use of SSBCs has not yet been investigated for most of the organic PSs under the WFD. Batch adsorption studies for all relevant PSs are required for the further development of SSBC applications. In terms of the circular economy, concepts should be developed for the combined production and application of SSBC at real WWTPs. Finally, the feasibility of those concepts should be tested by installing and operating SSBC production and adsorber pilot plants on WWTP sites.

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