



Benchmarking biochar with activated carbon for immobilizing leachable PAH and heterocyclic PAH in contaminated soils[☆]

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ABSTRACT

Remediation of residually contaminated soils remains a widespread problem. Biochar can immobilize polycyclic aromatic hydrocarbons (PAH). However, studies on its ability to immobilize PAH and N, S, and O substituted PAH (hetero-PAH) in real soils, and benchmarking with commercial activated carbon are missing. Here, we compared the ability of pristine biochar (BC), steam-activated biochar (SABC), and commercial activated carbon (AC) to immobilize PAH and hetero-PAH. The three carbons were tested on soils from four different contaminated sites in Austria. Different amendment rates (w/w) of the carbons were investigated (BC: 1.0, 2.5, and 5%; SABC: 0.5, 1.0, and 2.0%; AC: 1%) in batch experiments to cover meaningful ranges in relation to their performance. SABC performed better than AC, removing at least 80% PAH with the lowest application rate of 0.5%, and achieving a complete removal at an application rate of 1.0%. BC performed slightly worse but still acceptable in residually contaminated soils (40 and 100% removal at 1 and 5% amendment, respectively). The ability of BC and SABC to immobilize PAH decreased as the PAH-molar volume increased. PAH with three or more rings were preferentially removed by AC compared to SABC or BC. This can be explained by the difference in pore size distribution of the carbons which could limit the accessibility of PAH and hetero-PAH to reach sorption sites for π - π electron donor-acceptor interactions, which drive PAH and hetero-PAH sorption to carbons. Column percolation tests confirmed the results obtained in batch tests, indicating, that decisions for soil remediation can be derived from simpler batch experiments. In soil samples with 1% BC, a reduction of over 90% in the total concentration of PAH in the leached water was observed. Overall, BC and SABC were demonstrated to be valid substitutes for AC for stabilizing residually contaminated soils.

1. Introduction

Over 2.5 million locations in Europe are potentially polluted sites according to the European Commission. Therein, polycyclic aromatic hydrocarbons (PAH) account for 11% and 15% of soil and (ground)water contamination (EEA, 2009). Although hotspots of PAH-contaminated soils are frequently excavated and/or remediated, surrounding areas often remain residually contaminated. Such residually contaminated sites can

pose a risk to surrounding areas and (ground)water resources, as well as biota resulting in potential bioaccumulation in exposed organisms. PAHs are often found together with heterocyclic PAHs (hetero-PAHs), containing nitrogen (N), sulphur (S), and/or oxygen (O) substitutions (Achten and Andersson, 2015). A range of strategies exist to remediate PAH and hetero-PAH contaminated sites (Dai et al., 2022; Gan et al., 2009), but many of them require ex-situ treatment and are financially unviable for large and diffusely contaminated areas. This, together with the ongoing

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release of PAH and hetero-PAH into the environment, necessitates more cost-efficient techniques.

Natural and anthropogenic sources of PAH and hetero-PAH include wildfires and volcanic eruptions, as well as crude oil emissions, incomplete combustion of oil, coal, wood, and waste, traffic emissions, and industrial pollution, which continue to pose one of the most abundant types of soil, air and water pollution for remediation practitioners (Dai et al., 2022; Manzetti, 2013; Payá Pérez and Rodríguez Eugenio, 2018). Therein, polluted soil is mostly excavated and placed in landfills (“dig and dump”). The US Environmental Protection Agency (US EPA) listed 16 major PAH as priority pollutants in water in 1976 due to their carcinogenicity and ability to bioaccumulate; more recently PAH were also highlighted as important soil pollutants (USEPA, 2008). Over time, these 16 compounds have become the basis to assess PAH contamination in most legislative frameworks on PAH pollution globally. However, this list is not representative of the totality of hazardous polycyclic aromatic compounds. For example, it does not include any hetero-PAH which can be more mobile and toxic than their unsubstituted counterparts (Andersson and Achten, 2015; Brendel et al., 2018).

The use of commercial activated carbon for the stabilization of PAH contaminated soils and sediments is well-accepted in the remediation community (Beesley et al., 2011; Ghosh et al., 2011; Hale et al., 2012; Koitowski et al., 2017; Zelinska and Oleszczuk, 2016). Commercial activated carbon is typically produced from fossil carbon, coconut shells, or peat and activated either chemically by using e.g. ZnCl or via the more sustainable water steam (“physical activation”). A more sustainable biomass-based carbonaceous group of sorbents called “biochar”, produced from biomass pyrolysis without activation steps, has gained substantial attention over the last decade as potential substitutes of traditional activated carbons for immobilizing PAH (Esfandiari et al., 2021; Valizadeh et al., 2022; Zhou et al., 2022). In spite of the abundance of information on the immobilization of PAH by activated carbon and biochar (“carbons”), less is known about hetero-PAH immobilization (Sigmund et al., 2018). Hetero-PAH are largely neglected in the literature, and a comparison of biochar and activated carbon in complex environmental samples is lacking. Moreover, the majority of experiments failed to consider the complexity of real soils, including pollution composition and extent, ageing processes, and how the properties of the soil itself may affect the performance of carbons. To help close this knowledge gap, we compared the immobilization of PAH and hetero-PAH by a non-activated biochar (BC) a steam activated wood char (SABC), and a commercial activated carbon (AC), in four PAH-contaminated soils recovered from active remediation sites, using batch and column percolation tests. These results were then used to benchmark the performance of these carbons under conditions relevant for remediation practitioners.

2. Materials and methods

2.1. Materials

Anonymized soil samples from four different PAH and hetero-PAH contaminated sites in Austria were provided by ESW Consulting Wruss ZT GmbH, hereafter referred to as S1, S2, S3, and S4. To maintain the initial heterogeneity of the samples and following leaching standards DIN 19529 and EN 12457–4, soils were not pre-treated (e.g. drying, milling, sieving).

Three different carbons (Table 1) were used for subsequent PAH and hetero-PAH immobilization experiments: BC (commercially available biochar from mixed softwoods, Basna, Serbia), SABC (steam activated beech wood biochar, Ithaka Institute, Switzerland) and AC (Norit SAE super, commercial activated carbon produced from fossil feedstocks, Cabot Corporation, Latvia). AC was used as a benchmark material, as it is an activated carbon specifically produced and marketed for the sorption of organic contaminants in water. BC is a pristine wood-based biochar that has not undergone any modification, whereas SABC is a wood based biochar that has undergone steam activation. The two wood-based

Table 1
Summary of the production conditions of the applied carbons.

	Carbon	Activation	Feedstock	Thermal treatment	Temperature
BC	Biochar	None	Mixed woods	Pyrolysis	400–500 °C
SABC	Activated biochar	Steam	Beech wood	Pyrolysis	900 °C
AC	Activated carbon	Steam	Fossil feedstock	Pyrolysis	Unknown

biochars were selected over non-wood based materials because biochars produced from wood are known to be more aromatic and often also more porous compared to non-wood based biochars (Ippolito et al., 2020), which are often positively linked to PAH and hetero-PAH sorption.

Elemental composition (C, H, N, S) of soil samples and carbons was determined via elemental analyzer (Elementar VarioMacro). Total inorganic and organic carbon (TIC and TOC respectively) were measured using a multi-phase carbon analyzer, equipped with a solid-state infrared detector (LECO RC-612). The specific surface area (SSA) and pore volume (PV) of the carbons were measured via N₂ physisorption (Quantachrome Nova 2000 analyzer), after degassing overnight under vacuum at 105 °C (Sigmund et al., 2017).

2.2. Batch leaching and immobilization experiments

Carbons were added to soils at different proportions: 1.0% for AC; 0.5%, 1.0% and 2.0% for SABC; 1.0%, 2.5% and 5.0% for BC. Sorption batch experiments at two solid to liquid (S:L) ratios were carried out adding 100 g of any soil-carbon mixture to 200 mL (S:L ratio 1:2, DIN, 19529:2015–12) and 1000 mL (S:L ratio 1:10, EN 12457–4:2002) of deionized water. All measurements were compared to unamended soil samples (“control”) used to quantify readily leachable contaminant concentrations. Experiments under the same conditions with only carbons served as blank controls to ensure no PAH and hetero-PAH leached from the materials would affect the results from the sorption experiments. All samples were prepared in glass bottles with screw tops and placed on a shaker at 170 rpm. After 24 h of equilibration, samples were collected and centrifuged at 1000 g for 20 min. The supernatant was then split into two parts for PAH and hetero-PAH extraction. All experiments were performed using two replicates.

2.3. Percolation test

Column percolation tests were performed to validate batch measurements for a selection of scenarios following a guideline from the Austrian Environment Agency (Wimmer and Döberl, 2011), using glass columns with plastic caps (behr Labor-Technik, 60 × 320 mm). The base and top of the column were covered with a glass fiber filter (Whatman) to prevent the mobilization of soil and biochar, and to prevent the column from blocking. The columns were filled with 1.5 kg of contaminated soil. Four columns were prepared for each soil sample: two columns filled with soil only (“control”), and two with a mixture of soil and 1% BC. Soil-biochar mixtures were homogenized overnight using an end over end shaker before they were used to fill columns. Deionized water was percolated in an up-flow direction using a peristaltic pump at room temperature (20 °C) and was then collected in glass bottles. Flow rates ranged from 0.72 to 0.82 mL/min, depending on the individual soil transmissivity. Table 2 lists the nine S:L ratios used which ranged from 1:0.3 to 1:10 [kg/l]. Bottles were replaced each time the subsequent ratio was reached and were stored at 4 °C. To assess whether desorption of contaminants took place under pseudo-equilibrium conditions during the percolation process, the flow was interrupted for 24 h after the S:L ratios 1:3 and 1:7. After these interruptions an amount of percolation volume equivalent to one pore volume of the packed column was sampled.

Table 2

Solid to liquid ratios and percolation volumes used in the experiments based on sample pore volume (PV) and dry matter (DM), following a guideline from the Austrian Environment Agency (Wimmer and Döberl, 2011).

Fraction	S:L-ratio [kg/L]	Percolation volume [L]
1	1 : 0.3	0.3 * DM
2	1 : 1	0.7 * DM
3	1 : 2	1.0 * DM
4	1 : 3	1.0 * DM
stop 24 h		
5	PV	PV
6	1 : 5	2.0 * DM - PV
7	1 : 7	2.0 * DM
stop 24 h		
8	PV	PV
9	1 : 10	3.0 * DM - PV

2.4. Analysis of PAH and hetero-PAH

Water, acetonitrile and methanol (all HPLC grade) were purchased from PanReac AppliChem (Darmstadt, Germany), cyclohexane (Pestionorm®) from VWR (Pennsylvania, USA), ethylacetate (Picograde®) from Th. Geyer (Renningen, Germany). PAH-standards were purchased readily mixed at a concentration of 100 mg/L (PAH-mix 9) from LGC-Standards (Teddington, UK). Hetero-PAH-standards were obtained readily mixed at a concentration of 10 mg/L from Neochema (Bodenheim, Germany).

For PAHs determination, an internal standard mixture containing Naphthalene D8, Acenaphthene D10, Phenanthrene D10, Fluoranthene D10, Pyrene D10, Benzo [a]anthracene D12, Benzo [a]pyrene D12, and Dibenzo [a,h]anthracene D14 was prepared in cyclohexane, resulting in a final concentration of 20 µg/L of internal standards in the cyclohexane extraction agent. For extraction, 100 mL of supernatant from the batch experiment was mixed with 2.5 mL of extraction agent and placed in a glass vessel on a magnetic stirring plate for at least 30 min. An aliquot of the extracted solution was cleaned up via a cyclohexane pre-conditioned column containing glass wool, Al₂O₃ and Na₂SO₄. The cleaned up and pre-concentrated extract was then used for quantification via gas chromatography – mass spectrometry (GC-MS). PAH analysis was performed using an Agilent 7890 A GC equipped with a 5977 B MS, a MMI (multi-mode injector) and a 7693 autosampler, and a 30 mm × 0.25 mm I.D. ZB-5MSi column with 0.25 µm film (Phenomenex). The injection temperature was held for 5 s at 70 °C with a split flow of 60 mL/min. Afterwards the injector was heated up to 300 °C with a rate of 600 °C/min. Oven temperature was held for 40 s at 50 °C and afterwards heated up to 280 °C with a rate of 15 °C/min and further heated up to 300 °C with a rate of 5 °C/min. Temperature was held for 16 min. Helium was used as carrier gas with a column flow of 1.2 mL/min. The transferline was heated up to 280 °C, whereas the ion source was held at 230 °C and operated in EI mode. Quantification was done using two characteristic mass fragments. For all PAH-analytes a LOQ of 25 ng/L or less was achieved.

For the extraction of hetero-PAH, 20 µL of internal standard (Naphthalene D8, Anthracene D10, Fluorene D10, Chinolin D7, Dibenzofuran D8) were added to 400 mL of aqueous sample, which was then processed via SPE-DEX 4790 (solid phase extractor system, Horizon technology) using HLB-L discs. The extract was dried using Na₂SO₄ and concentrated with a solvent evaporator (Turbovap II, Biotage) to a volume of 1 mL. Thereafter, 500 µL of sample was mixed with 5 µL of sorbitol solution (10 mg/mL sorbitol in 80/20 v/v acetone/water) and analysed via GC-MS, while 10 µL of the sample was added to 1 mL of 10/90 v/v acetonitrile/water and analysed via liquid chromatography – mass spectrometry (LC-MS), described in more detail later. Both GC-MS and LC-MS were combined to cover a larger range of hetero-PAH structures. The hetero-PAH analysed via GC-MS are: Benzofurane, 2-Methylbenzofurane, Benzo(b)thiophene, 2,3-Dimethylbenzofurane, 2-Methylquinoline, 4-Methylquinoline, 3-Methylbenzothiophene, 1-

Methylisoquinoline, 2,6-Dimethylquinoline, 2,4-Dimethylquinoline, 2-Hydroxybiphenyl, Dibenzofurane, 2-Methylidibenzofurane, 4-Methylidibenzofurane, Xanthene, Dibenzothiophene, Carbazole, Xanthone, and Benzothiazole. The hetero-PAH analysed via LC-MS are: Quinoline, Isoquinoline, 1-Hydroxyisoquinoline, 2-Hydroxyquinoline, Acridine, 2-Hydroxy-4-Methylquinoline, Phenanthridinone and Acridinone.

For Hetero-PAH GC-MS analysis an Agilent 7890 A GC was used equipped with a 5975C MS, a PTV injector (Optic 3, GL Sciences) and a Combi PAL autosampler (CTC Analytics). A 30 m × 0.25 mm I.D. ZB-5MSi column with a film of 0.25 µm was used (Phenomenex). The injection temperature was held for 10 s at 50 °C with a split flow of 120 mL/min. Afterwards the injector was heated up to 280 °C with a rate of 420 °C/min. The oven temperature was held for 2 min at 50 °C and afterwards heated up to 320 °C with a rate of 15 °C/min. The temperature was held for 1 min. Helium was used as carrier gas with a column flow of 1.2 mL/min. The transferline was heated up to 280 °C, whereas the ion source was held at 230 °C and operated in EI mode. Quantification was done with two characteristic mass fragments. For all hetero-PAH-analytes a LOQ of 100 ng/L or less was achieved.

For Hetero-PAH LC-MS analysis a Shimadzu Nexera U-HPLC system was used equipped with a DGU-20 A degasser, two LC-30AD pumps and a CTO-20AC column oven. A Shimadzu LCMS 8060 triple quadrupole mass spectrometer was used with argon as the collision-induced dissociation (CID) gas. For ionization, an ESI interface was used. Nitrogen was supplied by a Parker LCMS30 generator. For separation a Kinetex C18 column (3 mm × 100 mm, 2.6 µm) by Phenomenex was used. The mobile phases were composed of water with 0.1% formic acid and methanol with 0.1% formic acid. The total flow was kept constant at 0.4 mL/min. Separation was done using a gradient profile. The run started with 5% methanol and held for 1 min. Then the gradient was raised up to 100% methanol during 9 min and held for 2 min. The nebulizing gas and the drying gas flow were set to 3.0 and 10 L/min, respectively. The oven temperature was adjusted to 45 °C and the CID gas pressure was set to 270 kPa. The MS was operated in the ESI+ and ESI- mode within the same run, with at least two transitions for each compound. For all hetero-PAH-analytes a LOQ of 100 ng/L or less was achieved. Measured recovery rates for both PAH and hetero-PAH analysis were generally above 95%, with variations in recovery being accounted for via the use of internal standards.

3. Results and discussion

Analysis of the aqueous phase in batch experiments with the unamended soils showed that soil S4 had the highest concentration of leachable contaminants: 3114 µg/kg of PAH (Σ of 16 EPA PAH) and 199 µg/kg of hetero-PAH (Σ of 27 measured compounds). The samples S1, S2 and S3 leached 129 µg/kg, 115 µg/kg, and 31 µg/kg PAH, and 58 µg/kg, 159 µg/kg, and 7 µg/kg hetero-PAH, respectively. Sample S2 was the only soil containing PAH with four fused aromatic rings or more.

Soil samples also differed in elemental composition and carbon content, with carbon content ranging from 2.5% for S4 to 7.0% for S3. Soils S2 and S3 contained the most organic carbon (Table 3). The measured specific surface area of AC, SABC and BC was 1176 m²/g, 507 m²/g, and 231 m²/g, respectively, total pore volume followed the same order. All carbons were highly aromatic with the molar H/C ratio being 0.198, 0.146, and 0.138 for BC, AC, and SABC, respectively.

3.1. Immobilization depends on molecular size and amendment rate

Batch tests were carried out with an S:L ratio of 1:2 and 1:10. Experiments with the 1:10 ratio in some cases showed less immobilization of PAH and hetero-PAH. Still, the results were in good agreement between both ratios. We here focus on the results of the 1:2 measurements, which can be considered a more realistic S:L ratio. Both 1:2 and 1:10 S:L experiments consistently showed complete removal of PAH from the leachate with the lowest carbon application rates tested (1.0% for BC,

Table 3

Characterization of contaminated soils used in this study.

ID	Elemental analysis				C type		\sum 16 EPA PAH	\sum 27 hetero- PAH
	C [%]	H [%]	N [%]	S [%]	TIC [%]	TOC [%]	[μ g/kg]	[μ g/kg]
S1	5.3	0.3	0.1	0.1	5.0	0.3	129	58
S2	4.6	0.5	0.1	1.2	2.7	2.1	115	159
S3	7.0	0.4	0.2	0.3	4.2	2.9	5	7
S4	2.5	0.7	0.0	0.1	3.3	0.8	3114	199

0.5% for SABC, 1.0% for AC) in most cases. The only exception was sample S4, which had the highest PAH and hetero-PAH contamination (3114 μ g/kg for \sum PAH and 199 μ g/kg for \sum hetero-PAH) and required a higher application rate (5%) to achieve nearly complete immobilization.

SABC performed better than AC (Fig. 1). Specifically, it removed >80% of PAH from soils S1, S2, and S4 using an application rate of 0.5%, and almost complete removal was achieved with 1.0% application. The even higher application rate was never significantly more beneficial. The immobilization rates achieved with 1% AC ranged between 68 and 99%. The superior performance of SABC compared to AC may be explained by its slightly higher aromaticity (lower H/C ratio) which increases the capacity of the carbon to sorb molecules via π - π electron donor-acceptor interactions, and differences in its pore size distribution. These factors superseded the importance of the higher specific surface area of AC compared to SABC. The BC generally also performed well, however it was not well suited to treat the highly contaminated S4 soil. For this sample, BC at an application rate of 1.0%, only achieved a 45% immobilization, and a >98% immobilization was only achieved with an application rate of 5.0%. Still, with the residually contaminated soil samples S1, S2, and S3, BC performed similarly to SABC.

For compounds with up to three aromatic rings, immobilization was similar across carbons. There were differences for PAH with more than three aromatic rings (found only in sample S2). These larger compounds, i.e., fluoranthene, benzo [a]anthracene, chrysene, benzo [b]fluoranthene, benzo [k]fluoranthene, benzo [a]pyrene, indeno [1,2,3-c,d]pyrene, dibenzo [a,h]anthracene, and benzo [g,h,i]perylene, were preferentially removed by AC compared to BC and SABC. Fig. 2 shows

the immobilization of each PAH in correlation to its molar volume for the three carbons at the same application rate (1.0%). For compounds with a molar volume <1.5 mL/mol, the immobilization achieved with BC and SABC was similar to AC. However, as the molar volume increased, there was an increasingly clear differentiation in sorption affinity, with AC being the strongest sorbent, followed by SABC and finally BC. This difference may be related to the pore size distribution of the three materials (Fig. 3). The distribution and availability of pores in carbons is critical because the absence or scarcity of mesopores could limit the availability of accessible PAH and hetero-PAH sorption sites for π - π electron donor-acceptor interactions, which drive PAH and hetero-PAH sorption to carbons (Yang et al., 2021; Zhu and Pignatello, 2005). The inability of a molecule to sorb due to its size is a phenomenon called size exclusion (Nguyen et al., 2007; Valizadeh et al., 2022; Xiao and Pignatello, 2015; Zhou et al., 2022). This phenomenon may partially explain why the sorption of compounds decreased as their molar volume increased for BC and partially also for SABC.

When normalizing the mass of immobilized PAH to the sorbent's specific surface area, SABC immobilized 431 ng/m², BC 406 ng/m², and AC 126 ng/m² in the soil with the highest concentrations of PAH and hetero-PAH (S4) at the same application rate (1%). In the same sample, immobilization was negatively correlated with molecular mass ($p < 0.05$) and molecular volume ($p < 0.05$) with SABC and BC ($p < 0.05$). SABC and BC thus immobilize more PAH than AC per m² of surface area, but as the size of the molecule increases, size exclusion hinders larger molecules from entering some of these materials pore space.

Hetero-PAH were found in S1, S2 and S4, whereas S3 contained only PAH and almost no hetero-PAH. All carbons proved effective in the immobilization of hetero-PAH, achieving an immobilization of at least 85% in all combinations, irrespective of the application rate (Fig. 4). With the highest application rate, total immobilization was achieved for all three soils. In soil S4, SABC and AC immobilized >90% of the pollutants with the lowest application rate (0.5% and 1%, respectively), whereas BC only with the highest application rate (5%).

Although it is difficult to establish a representative average price for biochar, it is generally considered cheaper than activated carbon (Hale et al., 2012; Lehmann et al., 2006; Thompson et al., 2016). This is because the production of biochar is less complex (no activation step) and uses less energy compared to activated carbon production. Indeed, biochar is considered a negative emission technology, which is encouraged to be used to store carbon in soil (Jeswani et al., 2022).

In some cases, their greater sorption capacity makes activated

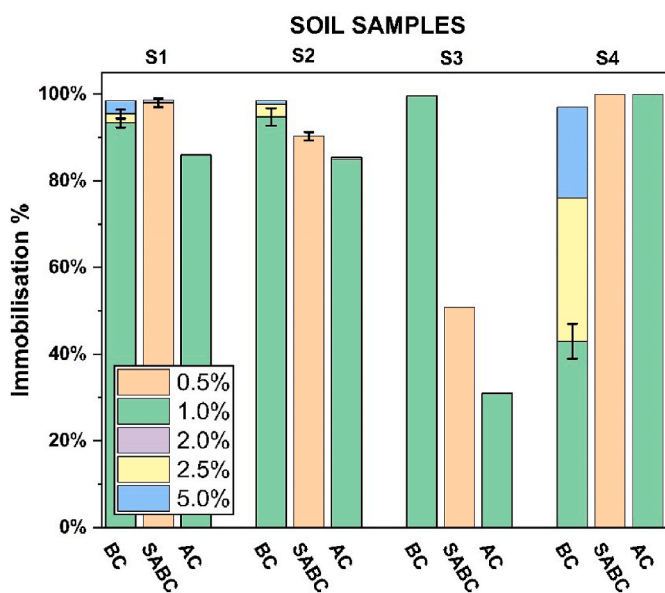


Fig. 1. \sum PAH immobilization (%) with S:L ratio 1:2, different carbons, and different application rates (SABC 0.5%, 1.0%, 2.0%/AC 1.0%/BC 1.0%; 2.5%, 5.0%).

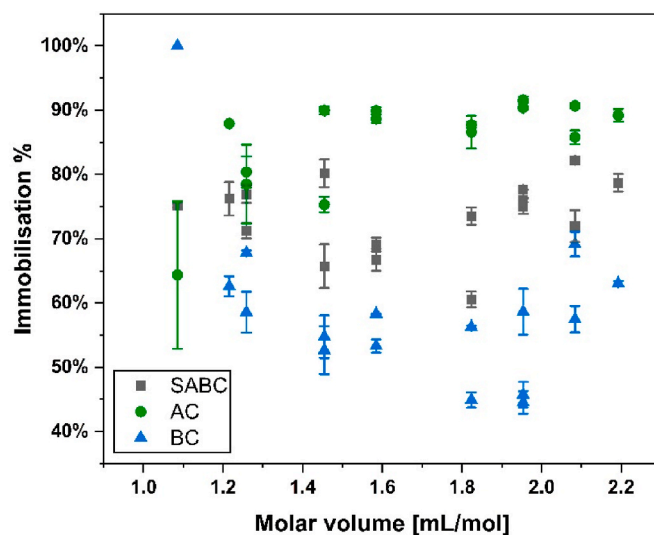


Fig. 2. Immobilization of PAH using SABC, AC and BC with the same application rate (1%) related to PAH molar volume shows a separation of trends with increasing molar volume (from left to right).

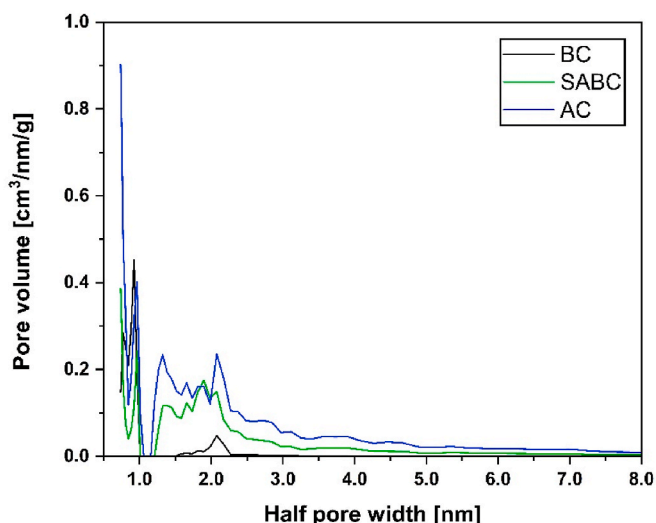


Fig. 3. Pore size distribution of AC (activated carbon), SABC (steam activated biochar), and BC (biochar).

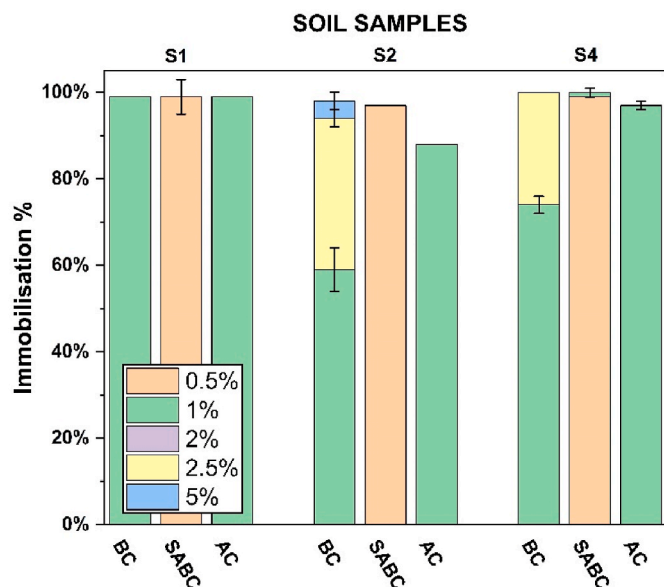


Fig. 4. Σ hetero-PAH immobilization (%) with S:L ratio 1:2, different carbons, and different application rates (BC 1.0%; 2.5%, 5.0%; SABC 0.5%, 1.0%, 2.0%; AC 1.0%).

carbons preferable to use. However, in many cases a well selected biochar and application rate results in a similar performance compared to commercial and less sustainable commercial activated carbons. Therefore, the applicability of biochar as a sustainable alternative to activated carbon was investigated in a more complex and realistic setup, using BC in a percolation test.

3.2. Column percolation test confirmed trends observed in batch experiments

Column percolation tests, which were used to validate findings from simplified batch test following a standardized protocol to investigate particularly challenging scenarios (Wimmer and Döberl, 2011), confirmed the results obtained from batch tests. The leachate samples containing a mixture of contaminated soil and 1% BC showed a maximum concentration of 2.2 $\mu\text{g/L}$ hetero-PAH and 2.0 $\mu\text{g/L}$ of PAH respectively, compared to 22.5 $\mu\text{g/L}$ of hetero-PAH and 25.7 $\mu\text{g/L}$ of

PAH from control columns without sorbent amendment. In both cases, the majority of mobilization occurred at a S:L ratio of 1:1, highlighting the high mobility of the PAH and hetero-PAH involved.

The addition of 1% BC immobilized over 90% of PAH and hetero-PAH in the percolation column experiments (Fig. 5). This further emphasizes the potential of biochar for preventing PAH and hetero-PAH mobilization from contaminated soils. During the percolation experiments two 24-h breaks were used to quantify contaminant desorption under pseudo-equilibrium conditions, during both of which no contaminant desorption was observed. This result has practical implications for remediation decision makers, as batch tests are less time and cost intensive to perform compared to column tests.

4. Conclusion

We here compared the suitability and performance of a biochar, a steam activated biochar and a conventional activated carbon to immobilize 16 PAH as well as 27 hetero-PAH in contaminated soils recovered from four different active remediation sites. Our findings show that using pristine or activated biochar can achieve similar or better organic contaminant immobilization at lower environmental costs compared to conventional activated carbon when immobilizing PAH and hetero-PAH in residually contaminated soils. An application rate of 1% biochar, steam activated biochar, or commercial activated carbon was found to be similarly effective in immobilizing a heterogeneous group of 16 PAH and 27 hetero-PAH. The main difference between wood based (activated) biochar and activated carbon was their ability to immobilize high molecular weight PAH, for which pore size distribution of wood based biochars may exclude larger molecules from accessing sorption sites within their pore space. Our study suggests that it can be advantageous to use biochar for the remediation of residually contaminated soils, as its use is encouraged not only to improve soil quality, but also as a carbon sink that can help decrease the environmental- and carbon footprint of soil remediation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

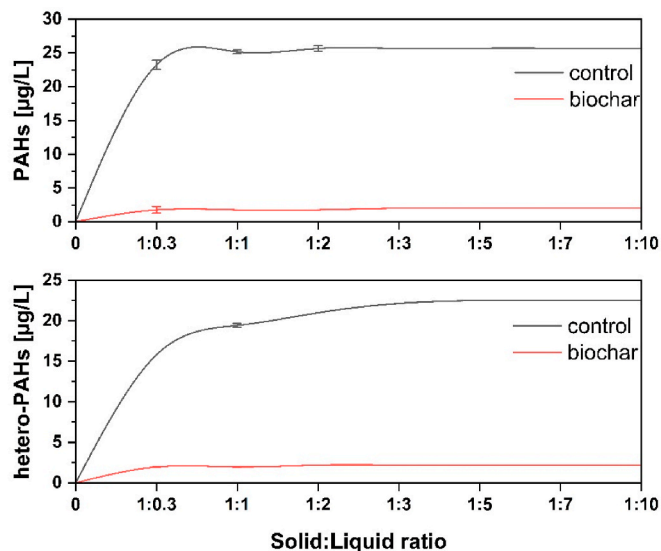


Fig. 5. Mobilization of PAH and hetero-PAH in column percolation test with (biochar) and without (control) 1.0% BC application.

Data availability

Data will be made available on request.

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