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*Link to article, DOI:*
10.11581/65841874-5e4c-4b7c-9197-b162b2b79e2d

*Publication date:*
2026

*Document Version*
Publisher's PDF, also known as Version of record

# Investigation of environmental issues related to the production and use of biochar

## Executive summary of feedstock and biochar analysis

**Raissa Rossi[1]; Giulia Ravenni[1]; Paulina Godlewska[1]; Clara Benedikte Mader Lade[2]; Kristin Kostadinova[2]; Heidi Birch[2]; Mikael Emil Olsson[2]; Philipp Mayer[2]; Pia Lassen[3]; Wolfgang Stelte[1]*.**

*[1] Catalysis and High-Temperature Engineering Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark*
*[2] Department of Environmental and Resource Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark*
*[3] Department of Environmental Science. Aarhus University. Frederiksborgvej 399. DK-4000 Roskilde, Denmark*

*Corresponding author: Wolfgang Stelte, wost@kt.dtu.dk

Publication date: 17th June 2026

This document provides a summary of the mid-term results delivered in December 2025 within the project "Investigation of environmental issues related to the production and use of biochar". The work was carried out by researchers from the Technical University of Denmark – Department for Chemical and Biochemical Engineering (DTU-KT), Department of Environmental and Resource Engineering (DTU Sustain), and Aarhus University – Department of Environmental Science (AU ENVS). The project is financially supported by the Danish Environmental Protection Agency (Miljøstyrelsen).

The project addresses environmental issues associated with producing and applying biochar on agricultural soils for biochar carbon removal (BCR) in Denmark, with a particular focus on contaminant risks, including persistent organic pollutants (POPs), other regulated organic contaminants, and heavy metals. The mid-term results comprise two complementary reports, summarized in this document. The first report quantifies contaminant inventories in Danish-relevant biomasses and their derived biochars, produced in both laboratory and industrial settings. The reported results are given as total concentrations, as all samples were subjected to intensive extraction procedures for quantification of contaminants. The second report evaluates aqueous exposure, sorption, and leaching of chemicals released from biochar through equilibrium batch tests and soil column experiments, thereby linking total contaminant inventories to mobility under water-contact and soil-amendment conditions.

# Part I - Comprehensive characterization of Danish biomass feedstocks and biochar

The project evaluated three feedstock categories—straw pellets, biogas residue fibers (BRF), and municipal sewage sludge—together with corresponding biochars produced under laboratory conditions (500–700 °C) and full-scale industrial conditions (including 600–800 °C configurations depending on feedstock).

The analytical program covered regulated and environmentally relevant contaminant groups, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), per- and polyfluoroalkyl substances (PFAS), bis(2-ethylhexyl) phthalate (DEHP), linear alkylbenzene sulfonates (LAS), nonylphenol ethoxylates (NPE), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F), and polychlorinated biphenyls (PCB). Removal efficiencies during pyrolysis were calculated using matched biomass–biochar pairs with ash-based yield correction.

Resulting biochars showed distinct inorganic fractions, with ash contents of 16.5% (straw), 41% (BRF), and 66% (sludge). Most samples complied with the EBC-Agro [1] H/C < 0.7 criteria, indicating biochars with a high carbon permanence. During pyrolysis, nitrogen was largely volatilized (~77% average loss, increasing with temperature). In contrast, phosphorus and potassium were mostly retained and enriched in the biochar, resulting in the highest phosphorus in sludge biochar (~66.000 mg/kg) and the highest potassium in BRF and straw biochars (~39.000 mg/kg).

Overall, laboratory- and industrial-scale biochars were broadly comparable, with no statistically significant differences for several contaminants (e.g., LAS, DEHP, dioxins). However, some scale-dependent differences were observed: Industrial biochar produced from wastewater sludge showed higher PAH and PFAS than laboratory samples produced from the same material, indicating potential process-related effects requiring further investigation.

Feedstock type was the main driver of biochar properties: straw biochar showed the most favorable overall contaminant profile, while sludge biochar exhibited the highest heavy metal levels but still low organic contaminant concentrations, demonstrating high removal efficiencies across matrices. Overall, organic contaminants were largely eliminated during pyrolysis, resulting in no statistically significant differences in biochar composition for these compounds, regardless of the feedstock origins.

Across the range 500–800°C (lab: 500–700°C), pyrolysis temperature showed limited influence on most contaminants, likely because the studied interval overlaps with (or is above) key volatilization/degradation ranges for many compounds. However, temperature did affect more volatile metals (e.g., Cr, Cd, As) and tended to increase PAH mass concentrations above ~600°C.

## Heavy metals (HM) in solids

Overall, heavy metals and metalloids generally remain in biochar at the same order of magnitude as in the feedstock, although they become more concentrated due to mass loss from organic matter removal. In some cases, heavy metal concentrations in biochar exceeded the regulatory thresholds for waste to soil soil application defined in Danish regulations (BEK nº 1001) [2]. Non-compliances were observed for biochar produced from higher-ash waste-derived feedstocks (BRF and sewage sludge). Specifically, on average, BRF biochar exceeded EBC-Agro for Cu (157 mg/kg > 100 mg/kg). Sludge biochar exceeded BEK n°1001 for Cd (0.98 mg/kg > 0.8 mg/kg) and Ni (40.5 mg/kg > 30 mg/kg) and exceeded EBC-Agro for Cu (984 mg/kg > 100 mg/kg) and Zn (1399 mg/kg > 400 mg/kg).

Importantly, total HM mass concentrations do not necessarily reflect bioavailability, as many metals may be immobilized within the biochar structure after pyrolysis through mechanisms such as ion exchange, surface complexation, and precipitation.

Partial volatilization may occur for more volatile elements such as Cd, Pb, As, Ag, but the degree of enrichment is mainly determined by the original HM content, and the chemical characteristics of the biomass matrix. The volatilization behavior of metals may also be influenced by the presence of elements such as chlorine, sulfur, and alkali metals, which can facilitate the formation of more volatile HM species.

Among the feedstocks evaluated, straw biochars showed the lowest HM content, while BRF displayed volatilization for selected metals (e.g., Cr, Pb, As, Zn), and sewage sludge biochars retained most of its original HM content. Iron (Fe) dominated across all biochars, representing 72.5–89% of the total HM measured, and HM enrichment in sludge closely followed ash enrichment, indicating a strong association with the inorganic fraction. Minor differences between lab- and industrial-produced biochar likely reflect variations in operating conditions, reactor design, and mechanical entrainment of fine particles.

## PAHs in solids

PAHs were detected in all investigated feedstock. Straw biomass contained, on average, 0.29 mg/kg (sum of 15 PAHs) and was described as unexpectedly contaminated, whereas BRF and sewage sludge showed higher concentrations of approximately 3–6 mg/kg.

Following pyrolysis, PAH concentrations in biochar were generally low, but exhibited clear feedstock- and process-dependent patterns.

Overall, 66% of the biochar samples contained <0.85 mg/kg PAHs, and 30 out of 32 samples complied with the European Biochar Certificate EBC-Agro threshold (<6 mg/kg), indicating that optimized pyrolysis can effectively reduce PAH concentrations even in contaminated feedstocks, and that most produced biochars meet EBC limit values.

Biochars derived from biogas residue fibers and sewage sludge showed net PAH removal, consistent with a reduction in PAH mass concentration from initially contaminated feedstocks. For biochar derived from BRF produced between 500 and 600 °C, the reported PAH removal efficiency was approximately 96%. Additionally, removal efficiency (*RE*) for sludge samples was approximately 59% for industrial biochar and 98% for lab scale biochar.

In contrast, straw-derived biochar showed net enrichment and formation of additional PAH congeners. Straw biochar contained 15 congeners compared with 6 congeners in straw biomass, and newly formed congeners accounted for 31% of the sum-15 PAH concentration in straw biochar. Enrichment increased with temperature in laboratory straw biochars, with an average enrichment factor of about 38% at 500 °C rising to 547% at 700 °C. At 600 °C, removal dominated for straw with a reported removal efficiency of 74%, while one industrial straw biochar showed a reported removal efficiency of 15%. Despite the enrichment behavior, straw biochar remained low in absolute PAH concentration (1.79 mg/kg, on average) and typically lower than PAH levels observed for biochars derived from sewage sludge or biogas residue fibers.

Overall, the results support the conclusion that PAH outcomes depend on both feedstock characteristics and process conditions.

A key quality-control result was the identification of one industrial biochar sample derived from BRF as a pronounced PAH outlier. This sample reached a sum of 15 PAHs of 43 mg/kg and exceeded the EBC PAH threshold applied in the report. The report links such exceedances to process-related mechanisms, including re-deposition of condensable organics onto the biochar when gas–solid separation is insufficient, highlighting the need for process and product control to prevent PAH contamination of the final biochar product.

## PFAS in solids

PFAS were quantified as sum-23 PFAS (23-PFAS) in both feedstocks and biochars. The mean PFAS concentration in the three types of feedstocks were of similar magnitude but differed in variability: BRF were lowest and most consistent (n = 18; mean 2485 ng/kg; SD 468 ng/kg), sewage sludge was higher and more variable (n = 4; mean 3501 ng/kg; SD 1398 ng/kg), and straw had the highest mean with wide scatter (n = 6; mean 4074 ng/kg; SD 1328 ng/kg), including two samples below quantification.

In the corresponding biochars, mean 23-PFAS concentrations were lower than in the biomass feedstocks and in the ng/kg range (233 ng/kg for straw biochar, 465 ng/kg for biochar derived from BRF, and 874 ng/kg for sewage sludge biochar), indicating substantial but incomplete PFAS removal from the solid phase during pyrolysis.

PFAS concentrations in all biochar samples were several orders of magnitude below the preliminary Danish waste-related thresholds for sludge to soil application (<0.4 mg/kg DM; 400.000 ng/kg DM) [2]. Only four samples showed quantifiable concentrations of Σ4-PFAS (PFOA, PFOS, PFNA, PFHxS),

all well below the Danish indicative limit (10.000 ng/kg DM), with maximum values of 718 ng/kg (sludge) and 239 ng/kg (BRF). Laboratory removal efficiencies were about 89% for biochars derived from biogas residue fibers, about 96% for sewage sludge biochars (below quantification limits), and about 78.5% for straw biochar.

Industrial biochars showed greater variability, including outliers around 2000 ng/kg (biochar derived from biogas residue fibers) and 4845 and 3087 ng/kg (sewage sludge biochar). Removal efficiencies calculated for industrial biochar samples ranged 44–94% for biochars derived from BRF and 34–66% for sewage sludge biochars, with one apparent negative value (−12%) attributed to sample heterogeneity.

The report also notes that residual PFAS in biochar were mainly short-chain compounds and that pyrolysis reduced the number of detectable PFAS congeners.

## PCDD/F and PCB in solids

For dioxins and furans (PCDD/F), the report detected 17-PCDD/F in all three biomass types, straw, BRF and sewage sludge, with the highest levels in sewage sludge.

Average 17-PCDD/F concentrations in biomass were about 3.6 ng/kg dry matter for straw, about 38 ng/kg for biogas residue fibers, and about 2,608 ng/kg for sewage sludge. WHO-TEQ followed the same pattern, with straw and biogas residue fibers at low values (≤0.09 ng TEQ/kg) and sewage sludge averaging about 17 ng TEQ/kg (with an outlier around 48 ng TEQ/kg).

After pyrolysis, 17-PCDD/F was reduced by 96–99.99% when comparing biochar with the corresponding biomass, and biochar WHO-TEQ values were reported at 0.01–0.02 ng TEQ/kg. All analyzed biochars were below the established threshold by EBC-Agro and the EU fertilizing regulation (20 ng/kg of the 17-PCDD/F) used for comparison in the report, supporting the conclusion that pyrolysis can strongly mitigate PCDD/F-related risk in the solid biochar product under the investigated conditions.

For PCB, all biomass samples were below the quantification limit (<0.01 mg/kg dry matter). In biochar, only trace PCB was detected in one sample (PCB 118 at 0.02 mg/kg dry matter in one biochar derived from BRF), while all other biochars were below quantification.

The report therefore concludes that the investigated feedstocks did not produce systematically PCB-contaminated biochar, while noting that the dataset is limited by the very low detection frequency.

## DEHP, LAS, and NPE in solids

For bis(2-ethylhexyl) phthalate (DEHP) and linear alkylbenzene sulfonates (LAS), the report indicates that these contaminants were primarily relevant for sewage sludge, where both were present in the raw biomass and substantially reduced by pyrolysis. In sewage sludge-derived material, average

removal efficiencies were reported as approximately 88.5% for DEHP and about 99% for the sum of eight LAS congeners. The report further notes that these high removal efficiencies did not show a clear temperature dependence within the investigated conditions.

For straw and BRF, DEHP and LAS were generally at very low levels, and the report found no statistically significant differences between the raw biomasses and the corresponding biochars, consistent with low initial contamination and/or concentrations close to detection limits. Nonylphenol ethoxylates (NPE) were not detected in any of the analyzed biomasses or biochars. Overall, the report concludes that, under the investigated conditions, pyrolysis functions as an effective treatment step for DEHP and LAS in sludge-derived feedstocks and results in low residual concentrations in the biochar product.

# Part II - Sorption, leaching, and persistence of chemicals released from biochar

The second report evaluates contaminant exposure and leaching as the combined outcome of changes in contaminant mass concentrations and sorption properties induced by pyrolysis. Central endpoints include aqueous equilibrium concentrations, chemical activities (for volatile and semi-volatile organics), and leachate concentrations from soil columns under amendment scenarios scaled to the Danish phosphorus application limit (1xP, 10xP, 100xP). This provides a mobility-focused complement to the inventory-focused contaminant measurements in the first report.

## Chemical activities of (semi)volatile organics

Chemical activities of volatile and semi-volatile organics were measured using automated Headspace Solid Phase Microextraction (HS-SPME) that was coupled to GC-MS operated in scan mode. The report shows that the pyrolytic conversion from sewage sludge to biochar dramatically reduced the chemical activities across the entire chromatogram and that HS-SPME above biochars yielded signals near blank levels under the applied conditions. Biogas residue fibers showed lower overall signals than sewage sludge, and pyrolysis similarly reduced chemical activities. These results support the conclusion that pyrolytic conversion of feedstock to biochar reduces the potential of (semi)volatile organic to partition from the solid matrix.

## PAHs in water

Aqueous PAH exposure was assessed in equilibrium batch experiments for two sewage sludge feedstocks and matched sludge biochars by measuring freely dissolved concentrations of the 16 EPA

PAHs using immersion SPME coupled to GC–MS (SIM mode). The systems were equilibrated for seven days at 10 °C and analyzed after centrifugation. Calibration standards covered 0.001–1 µg/L.

In sludge suspensions, 15 of the 16 EPA PAHs were quantifiable, demonstrating that raw sludge can release a broad PAH spectrum into water under the applied conditions. Pyrolysis decreased aqueous concentrations markedly for every measured PAH in both sludge cases, indicating reductions in PAH exposure and leaching according to Equilibrium Partitioning theory. The report interprets this consistent decline as resulting from both reduced solid-phase PAH concentrations after pyrolysis and increased sorption strength of the biochar matrix, which limits partitioning into the aqueous phase. In addition, partial physical incorporation of PAHs into the biochar matrix during pyrolysis may further limit their mobility, contributing to the observed reduction in aqueous concentrations. Some higher-molecular-weight PAHs remained detectable in biochar suspensions despite the overall reduction, consistent with low but measurable residual release from a highly sorbing matrix rather than elevated exposure relative to the parent sludge.

## PFAS in water

Aqueous PFAS exposure was evaluated in equilibrium batch leaching experiments using matched sewage sludge and sludge-derived biochar. Under high-loading, near-equilibrium conditions, aqueous PFAS concentrations were consistently in the low ng/L range or below the analytical quantification limits.

When sludge was compared directly with its corresponding biochar, aqueous concentrations were generally lower after pyrolysis, indicating reduced PFAS release to water from the biochar matrix. The report also notes that the reduction was compound-specific, with several PFAS showing statistically lower aqueous concentrations in biochar than in tests on the parent sludge, while short-chain PFAS close to quantification limits could deviate from the overall trend.

Overall, the findings support the conclusion that pyrolysis tends to reduce aqueous PFAS exposure from sludge-derived material, while residual PFAS remain detectable at very low levels.

## Soil column leaching of PFAS

In soil column experiments with sandy soil amended with crushed sludge-, biogas-residue-fiber-and straw-derived biochars at 1xP, 10xP, and 100xP, measured PFAS in leachates originated predominantly from the soil matrix rather than the biochar.

At 1xP, biochar amendments had very limited influence on PFAS leaching across all three biochar types. At higher amendment levels, PFAS leaching even decreased for 2 out of 3 tested biochars, supporting the interpretation that biochar acted predominantly as a sink rather than a source for PFAS under the tested conditions.

## Heavy metals in water and soil column leaching

In general, biochars exhibited stronger sorption (i.e. higher $K_D$) and correspondingly lower aqueous-phase metal concentrations than their respective feedstocks, thus indicating decreased leachability after pyrolysis. This effect was more pronounced for sewage sludge derived biochars than for BRF derived biochars. While most metals demonstrated strong solid-phase association, certain elements, particularly Mo, V, and Sb—consistently exhibited lower $K_D$ values and thus greater relative mobility.

Metal concentrations in leachates from column experiments were generally low compared to environmental quality standards (Danish quality standards for drinking water) for biochar obtained from WWTP sludge, biogas residue fiber and straw. However, a formal risk assessment comparing the measured concentrations against environmental quality standards is still ongoing. The effect of the biochar amendment on the metal concentrations in the leachates was very limited at 1xP amendments for all three types of biochar. Metal concentrations in leachates generally increased at 10xP and 100xP biochar amendments, and the observed increases were biochar and metal specific.

Pyrolytic conversion will transfer most metals from feedstock to biochar, and these metals cannot be degraded in the environment. It is therefore crucial to avoid biochar amendments that are leading to environmental metal contaminations, which in turn might ask for setting quality standards for hazardous metals based on concentrations in feedstock, biochar or aqueous elutriates.

## Non-target screening of polar organics

Non-target screening of polar organic mixtures was conducted on aqueous leachates from equilibrium batch experiments using reverse-phase LC–HRMS (Orbitrap). In matched feedstock–biochar comparisons, biochar leachates consistently showed much lower total ion chromatogram signals than the corresponding feedstock leachates, indicating an overall reduction in polar organic signals released to water after pyrolysis. Feature detection initially yielded thousands of peaks per comparison and was refined using a structured filtering workflow including signal-to-noise and minimum intensity thresholds, blank subtraction, and peak-quality criteria. After filtering, most retained features still showed lower peak areas in biochar leachates than in feedstock leachates.

The report treats this as evidence of broadly reduced aqueous mobility of polar organics after pyrolysis and identifies the next step as focusing on the smaller subset of features that remain unchanged or appear higher in biochar leachates as candidates for persistent or pyrolysis-formed compounds.

## References

[1] European Biochar Certificate (EBC) (2012–2025) *European Biochar Certificate – Guidelines for a Sustainable Production of Biochar (Standard 10.5E)*. Carbon Standards International (CSI), Frick, Switzerland. Available at: https://www.carbon-standards.com/docs/transfer/4000093EN.pdf?t=864403

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