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| Agronomic efficiency | Buss W, Wurzer C, Bach M, Heberling J, Appel T, Gerber H, Mašek O. Highly efficient phosphorus recovery from sludge and manure biochars using potassium acetate pre-treatment. J Environ Manage. **2022** Jul 15;314:115035. doi: 10.1016/j.jenvman.2022.115035. Epub 2022 Apr 15. PMID: 35436706. | 2024, 2025, 06.02.26 | **no** | P content of SS Biochar ca reach up to 80% NAC solubility |
| | „P-Düngewirksamkeit von Klärschlamm-Rezyklaten“ Abschlussbericht 06.10.**2022** Dr. F. Jacobi D. Koch J. Löber C. Schumann Landesbetrieb Hessisches Landeslabor, Landesbetrieb Landwirtschaft Hessen, https://llh.hessen.de/wp-content/uploads/2025/09/abschlussbericht_p-duengewirksamkeit_von_klaerschlamm-rezyklaten_0.pdf | not sent | **no** | P content of SS Biochar ca reach up to 80% NAC solubility |
| | | | | |
| PFAS degradation | Kundu, S., Patel, S., Halder, P., Patel, T., Marybali, M. H., Pramanik, B. K., Praz-Ferreiro, J., Figueiredo, C. C., Bergmann, D., Surapaneni, A., Megharaj, M., Shah, K., Removal of PFASs from biosolids using a semi-pilot scale pyrolysis reactor and the application of biosolids derived biochar for the removal of PFASs from contaminated water, Environ. Sci.: Water Res. Technol., **2021**, 7, 638–649 | 2024, 2025, 06.02.26 | **yes** | **Degradation > 90 %** of PFOS and PFOA |
| | Eben D. Thoma, Robert S. Wright, Ingrid George, Max Krause, Dario Presezzi, Valentino Villa, William Preston, Parik Deshmukh, Phil Kauppi & Peter G. Zemek (**2022**): Pyrolysis processing of PFAS-impacted biosolids, a pilot study, Journal of the Air & Waste Management Association, https://doi.org/10.1080/10962247.2021.2009935 | 2024, 2025, 06.02.26 | **no** | **No PFAS** in Biochar found |
| | Sormo, E., Castro, G., Hubert, M., Licul-Kucera, V., Quintanilla, M., Asimakoupolos, A. G., Cornelissen, G., Arp, H. P. H., The decomposition and emission factors of a wide range of PFAS in diverse, contaminated organic waste fractions undergoing dry pyrolysis, Journal of Hazardous Materials 454, **2023**, 131447, https://www.sciencedirect.com/science/article/pii/S0304389423007306 | 2024, 2025, 06.02.26 | **yes** | **PFAS removal >96%** |
| | Jaroslav Moško, Helmut Gerber, et al.: PFAS removal >99% in biosolids biochar in a screw reactor as a function of residence time and temperature (500°C, 600°C, 700°C, 5min, 10 min, 15 min residence time). Results in publication process. Information on results available in person/online meeting: moskoja@vscht.cz.(Czech Academy of Sciences, **2026**) | 06.02.2026 | **no** | **PFAS removal >99%** in all parameters |
| | Mcnamara, P., Samuel, M.S., Sathyamoorthy, S., Moss, L., Valtierra, D., Lopez, H.C., Nigro, N., Somerville, S., Liu, Z. (**2023**). Pyrolysis transports, and transforms, PFAS from biosolids to pyliquid. Environmental Science: Water Research & Technology, 9, 386-395. https://doi.org/10.1039/D2EW00677D | 2024, 2025, 06.02.26 | **no** | PFAS **removal >99%** |
| | U.S. Environmental Protection Agency (EPA) Research Brief January **2021**, Potential PFAS destruction technology: Pyrolysis and gasification. https://www.epa.gov/sites/default/files/2021-01/documents/pitt_research_brief_pyrolysis_final_jan_27_2021_508.pdf | 2024, 2025, 06.02.26 | **no** | PFAS in Biochar **below detection limits** |
| | Bamdad, H.; Papari, S.; Moreside, E.; Berruti, F. High-Temperature Pyrolysis for Elimination of Perand Polyfluoroalkyl Substances (PFAS) from Biosolids. Processes **2022**, 10, 2187. https://doi.org/10.3390/pr10112187 | 2024, 2025, 06.02.26 | **no** | PFAS removal **>97%** |
| | Hušek, M., Semerád, J., Skoblia, S. et al. Removal of per- and polyfluoroalkyl substances and organic fluorine from sewage sludge and sea sand by pyrolysis.Biochar 6, 31/**2024** https://doi.org/10.1007/s42773-024-00322-5 | 2025, 06.02.2026 | **no** | PFAS in Biochar >500°C **below detection limits** |
| | Arturo A. Keller, Weiwei Li, Yuki Floyd, James Bae, Kayla Marie Clemens, Eleanor Thomas, Ziwei Han, Adeyemi S. Adeleye,Elimination of microplastics, PFAS, and PPCPs from biosolids via pyrolysis to produce biochar: Feasibility and techno-economic analysis. Science of The Total Environment, Volume 947, **2024**, 174773, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2024.174773 . | 2025, 06.02.26 | **no** | **Degradation >99 % of PFAS** microplastics and PPCPs |
| | Sid Ahmed Kessas, Helen Coarita Fernandez and Hugues Vanden Bossche, 19th IWA Conference on Sludge Management and at the NORDIWA **2025** Conference. The results are currently under publication.<br>Further information can be discussed during an online or in person meeting: sid-ahmed.kessas@suez.com (SUEZ Engineering & Construction)<br>https://european-biosolids.com/2025/session/3251034/pyrocarbonisation-of-wwtp-biosolids-effect-of-the-thermal-treatment-on-the-contaminants-of-emerging-concern-behavior-agronomic-properties-of-the-biochar#:~:text=Description,Authors | 06.02.2026 | **no** | PFAS in Biochar **below detection limits** |
| | Nimesha Rathnayake, Anithadevi Kenday Sivaram, Ibrahim Gbolahan Hakeem, Sudhakar Pabba, Savankumar Patel, Rajender Gupta, Jorge Paz-Ferreiro, Abhishek Sharma, Mallavarapu Megharaj, Aravind Surapaneni, Kalpit Shah **(2025)**: The fate of per- and polyfluoroalkyl substances (PFAS) during pyrolysis and co-pyrolysis of biosolids with alum sludge and wheat straw, Journal of Analytical and Applied Pyrolysis, Volume 187, ISSN 0165-2370, https://doi.org/10.1016/j.jaap.2025.106970. | new | **no** | Biosolids pyrolysis at 600 ℃ achieved **> 99 % PFAS destruction** under sufficient residence time |
| | Felizitas Schlederer, Edgar Martín-Hernández, C. Vaneeckhaute, Journal of Environmental Management, **2024**: Ensuring safety standards in sewage sludge-derived biochar: Impact of pyrolysis process temperature and carrier gas on micropollutant removal. https://doi.org/10.1016/j.jenvman.2023.119964 | new | **no** | PFAS was reduced **below detection limits** in sewage sludge pyrolysis at 650°C with N2 carrier gas, aligning with IBI and EBC guidelines. |
| | Buss, Wolfram **2021**: Pyrolysis Solves the Issue of Organic Contaminants in Sewage Sludge while Retaining Carbon—Making the Case for Sewage Sludge Treatment via Pyrolysis, ACS (American Chemical Society) Sustainable Chemistry & Engineering https://pubs.acs.org/doi/10.1021/acssuschemeng.1c03651 | new | **no** | The papaer covering 20 studies and more than 100 different organic pollutants demonstrate that pyrolysis reduces the concentration of well-established contaminants, such as PAHs, PCBs, and dioxins, but also emerging ones, i.e., pharmaceuticals, hormones, antibiotics, antibiotic resistance genes, antimicrobials, microplastics, and per- and polyfluoroalkyl substances (PFAS) with very high efficacy (>95 to **>99%** in most cases) |

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|---|---|---|---|---|
| | Sid-Ahmed Kessas, Helmut Gerber, Helen Coarita Fernandez and Hugues Vanden Bossche presented their work at BIO 360 (Nantes **2026**)<br>The results are currently under publication.<br>Further information can be discussed during an online or in person meeting: sid-ahmed.kessas@suez.com (SUEZ Engineering & Construction). Bio360 conference proceedings, Nantes, France. 12.02.2026<br>https://www.bio360expo.com/ConferenceList.aspx?eid=561&mid=389&sec=0&date=all&topic=&iti=&aid=1440&view=thumbnails | 06.02.2026 | **no** | Biochar of industrial pyrolysis plant analyzed in two different laboratories, ALS France & Eurofins Germany. The focus was on 50 different PFAS compounds. **NO PFAS** detected in Biochar at 600°C and 10min. |
| | The PFAS roadmap–Navigating a path together to improved management<br>Lokesh P Padhye*, Melanie Kah, Erin M Leitao, Karl Bowles, Paul Nathanail, Ian T Cousins, Romain Figuière, Bradley O Clarke, Jordan M Partington, Wejdan Alghamdi, Elsie M Sunderland, Bridger J Ruyle, Satoshi Endo, Trevor N Brown, Zhengyang Wang, Size Zheng, Joseph J Pignatello, Sanne J Smith, Marcel Riegel, Hans Peter H Arp, Jens Blotevogel, Robert J Giraud, Anthony K Rappé, Erlend Sørmo, Gerard Cornelissen, Marc A Deshusses, Igor V Novosselov, P Lee Ferguson, Brian R Pinkard, Timothy J Strathmann, Kapish Gobindlal, Jonathan Sperry, Elisabeth Cuervo Lumbaque, Nick Duinslaeger, Jelena Radjenovic and James Hatton<br>Published 16 February **2026** • © 2026 The Author(s). Published by IOP Publishing Ltd<br>Sustainability Science and Technology, Volume 3, Number 1<br>Citation Lokesh P Padhye et al 2026 Sustain. Sci. Technol. 3 012501<br>DOI 10.1088/2977-3504/ae286f | 20.02.2026 | **no** | Pyrolysis of PFAS-contaminated organic waste into biochar and its subsequent use as a PFAS sorbent could remove a significant amount of PFAS from environmental circulation |
| | | | | |
| Adsorption of environmental pollutants / Soil remediation | K. Kaetzl, M. Riegel, B. Joseph, R. Ossenbrink, H. Gerber, W. Gwenzi, T. Morck, D. Laner, T. Heinrich, V. Kromrey, K. Friedrich, M. Wachendorf, K. Stenchly, Biogenic Activated Carbons from Conservation Grassland Biomass for Organic Micropollutants Removal in Municipal Wastewater, Environmental Science and Ecotechnology,( **2025**) https://doi.org/10.1016/j.ese.2025.100588. | 11.02.2026 | **no** | Biochar traps and removes organic pollutants |
| | A Virtuous Cycle of Phytoremediation, Pyrolysis, and Biochar Applications toward Safe PFAS Levels in Soil, Feed, and Food, Gerard Cornelissen, Nathalie Briels, Thomas D. Bucheli, Nicolas Estoppey, Andrea Gredelj, Nikolas Hagemann, Sylvain Lerch, Simon Lotz, Daniel Rasse, Hans-Peter Schmidt, Erlend Sørmo, and Hans Peter H. Arp, Journal of Agricultural and Food Chemistry **2025** 73 (6), 3283-3285, DOI: 10.1021/acs.jafc.5c0065, https://pubs.acs.org/doi/full/10.1021/acs.jafc.5c00651 | 11.02.2026 | **no** | Biochar can be used for remediation of PFAS polluted farmland. |
| | Erlend Sørmo, Clara Benedikte Mader Lade, Junjie Zhang, Alexandros G. Asimakopoulos, Geir Wold Åsli, Michel Hubert, Aleksandar I. Goranov, Hans Peter H. Arp, Gerard Cornelissen, Stabilization of PFAS-contaminated soil with sewage sludge- and wood-based biochar sorbents, Science of The Total Environment, Volume 922, **2024**, 170971, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2024.170971 | 11.02.2026 | **no** | Sewage sludge biochars could be suitable sorbents for the ex situ stabilization and in situ remediation of PFAS-contaminated soil |
| | | | | |

# Assessment of PFAS Destruction Efficiency in a Full-Scale Sewage Sludge Pyrocarbonization Process

Sid Ahmed KESSAS[1], Helen COARITA FERNANDEZ[1], Marcel RENSMANN[2], Helmut GERBER[2], Hugues VANDEN BOSSCHE[1].

1. SUEZ Engineering & Construction, SUEZ International, Altiplano, 4 Place de la Pyramide, 92800 Puteaux, France
2. PYREG GmbH, Dörth, Germany.

Corresponding author: sid-ahmed.kessas@suez.com

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## INTRODUCTION

Pyrocarbonisation has emerged as a highly effective technology for the destruction of organic pollutants present in a wide range of waste materials. In recent years, growing scientific evidence has demonstrated its capability to address contaminants commonly found in sewage sludge, with particular emphasis on per- and polyfluoroalkyl substances (PFAS).

Multiple studies have shown that PFAS are effectively decomposed during sludge pyrolysis, resulting in their absence or presence below detection limits in the produced biochar. For example, Kundu et al. (2021) reported that more than 90 % of PFOS and PFOA were destroyed through an integrated pyrolysis–combustion process applied to sewage sludge [1].

Experimental and full-scale data provided by the US EPA Office of Research and Development further support these findings. Investigations conducted at a commercial pyrolysis facility operated by Bioforcetech using PYREG technology demonstrated that pyrolysis at approximately 600 °C with a residence time of 10 minutes, followed by combustion of the pyrolysis gases at 850 °C, resulting in complete PFAS removal from sewage sludge solids. In the same study, all 38 monitored PFAS compounds were either removed or reduced to levels below analytical detection limits in the resulting biochar [2,3].

Operational experience from the Fårevejle wastewater treatment plant in Denmark has confirmed these results at full scale. Pyrolysis of sewage sludge at temperatures between 600 and 650 °C with residence times exceeding 3 minutes, combined with subsequent incineration of pyrolysis gases at 850 °C for more than 2 seconds, led to the elimination of all seven previously detected PFAS compounds. Repeated trials consistently showed PFAS concentrations below detection limits in both biochar and flue gas emissions [4].

Comprehensive studies by Sørmo et al. (2023), covering several full-scale pyrolysis installations and four sewage sludge feedstocks, revealed PFAS reductions of one to three orders of magnitude in the biochar relative to untreated materials. Removal efficiencies exceeded 96 % at 500 °C and surpassed 98 % at temperatures of 700 °C and higher. The authors concluded that pyrolysis temperatures of at least 600 °C are required to ensure effective degradation of PFAS and other organic micropollutants to non-detectable levels [5].

General

The thermal oxidation of pyrolysis gases plays a key role in preventing PFAS release. A US EPA study (2023) evaluated PFAS destruction efficiency by comparing influent concentrations to gaseous, liquid, and solid emissions from high-temperature incineration. Destruction efficiencies exceeding 99.999 % were achieved for most quantifiable PFAS, with no detectable fluorinated products of incomplete destruction, indicating near-complete mineralisation [6].

Similarly, McNamara et al. (2023) reported that pyrolysis of biosolids at temperatures ranging from 500 to 800 °C removed more than 99 % of targeted PFAS and precursor compounds from the solid phase. Notably, among several innovative technologies evaluated, sludge pyrolysis was the only technique reaching a Technology Readiness Level (TRL) > 7, corresponding to operation in a real industrial environment [7].

Field data from a full-scale pyrolysis plant in California further demonstrated PFAS degradation to non-detectable levels in biochar, flue gas, and scrubber water when sludge was treated at 600 °C with subsequent thermal oxidation at 850 °C. Fourier transform infrared spectroscopy (FTIR) screening confirmed that all monitored C1–C8 PFAS species were below detection limits in the flue gas [8,9].

Laboratory-scale and pilot studies consistently support these operational results. High-temperature pyrolysis experiments conducted by Bamdad et al. (2022) achieved PFAS reductions of approximately 97–100 wt % in biochar produced at 700 °C [10], while Hušek et al. (2024) demonstrated that temperatures above 400 °C are required for effective PFAS and organically bound fluorine removal from sewage sludge [11]. Most recently, Keller et al. (2024) confirmed that pyrolysis eliminates more than 99 % of PFAS, microplastics, and pharmaceutical contaminants from biosolids, while enabling potential resource recovery through biochar valorisation [12].

The objective of this study was to evaluate the destruction efficiency and phase distribution of PFAS during full-scale sludge pyrocarbonization, including solid & gas streams. In addition, the study aimed to assess the ability of pyrolysis combined with complete oxidation of pyrolysis gases to produce a PFAS-free biochar suitable for safe and sustainable resource recovery.

## MATERIALS AND METHODS

The PYREG PX750 system at Kleve operates with a two-stage destruction process:

- Stage 1 — Carbonisation reactor: ~600 °C, 15–20 min residence time (oxygen-limited pyrolysis). Feedstock: municipal sewage sludge, pre-dried to >80% dry solids via belt dryer (60–100 °C). Input dry matter: 19.7% (raw sludge), 92.4% (dried sludge before reactor).
- Stage 2 — FLOX® flameless thermal oxidation (WS Wärmeprozesstechnik): 950–1050 °C at reactor outlet. Integrated wet scrubber and post-scrubber gas cleaning downstream.

The combustion flue gases generated from pyrolysis gas are cooled and dedusted, then treated by an acid scrubbing column followed by an activated carbon tower before being released to the atmosphere.

10 sampling points covering all solid (dewatered sludge, dry sludge, biochar, siloxane ashes), gaseous (pyrolysis gas, exhaust gas before and after scrubber and at the stack), and liquid phases (Scrubber water before & after the column) — the most comprehensive multi-phase PFAS characterization conducted on a PYREG system to date.

PFAS concentrations in solid matrices (dried sludge, biochar and ash) were determined by ALS France using accredited analytical methods based on solid-phase extraction followed by liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS). A comprehensive target list of approximately 50 PFAS compounds was

analyzed, including perfluorocarboxylic acids (PFCAs), perfluorosulfonic acids (PFSAs), fluorotelomer sulfonates, sulfonamides and selected PFAS substitutes, with compound-specific limits of quantification in the µg·kg$^{-1}$ range.

Gas-phase PFAS measurements were performed by INERIS, with chemical analyses subcontracted to EUROFINS Analyses de l'Air. Semi-volatile PFAS (55 target compounds) were sampled using a multi-stage trapping system (filters, adsorption resins and absorption solutions) and analyzed according to US EPA OTM-45, implemented under the French standard XP X 43-126. These analyses were conducted under COFRAC accreditation, using LC-MS/MS for compound-specific quantification.
In parallel, volatile fluorinated compounds and volatile PFAS (30 target compounds) were collected in passivated stainless-steel canisters and analyzed in accordance with US EPA OTM-50 using gas chromatography coupled to mass spectrometry (GC-MS). Additionally, trifluoroacetic acid (TFA) was quantified separately in condensates and absorption solutions using dedicated laboratory methods.

PFAS concentrations in the liquid effluent at the scrubber outlet were measured in accordance with the French regulatory framework for urban wastewater, as defined by the decree of 3 September 2025 on the analysis of per- and polyfluoroalkyl substances (PFAS) in influent and effluent waters of urban wastewater treatment plants. The analytical method was based on solid-phase extraction (SPE) followed by liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS). The analytical scope covered the 22 PFAS included in the regulatory list and was additionally extended to include trifluoroacetic acid (TFA).

Quality assurance included field blanks, isotopically labeled internal standards, recovery and breakthrough controls, and systematic reporting of detection and quantification limits.

## RESULTS AND DISCUSSION

ALS France analysed 50 PFAS compounds across raw sludge (SP-1), dried sludge (SP-2), biochar product (SP-3), and filter siloxane ashes (SP-4). Key findings are presented below:

**Table 1: Kleve WWTP — Solid Phase PFAS Results (µg/kg wet weight).**

| PFAS Compound | SP-1 Raw Sludge (µg/kg) | SP-2 Dried Sludge (µg/kg) | SP-3 Biochar (µg/kg) | SP-4 Ashes (µg/kg) |
|---|---|---|---|---|
| PFOS (dominant) | 0.91 | 2.10 | <0.3 | <0.3 |
| Capstone B (6:2 FTAB) | 1.10 | <1.0 | <2.0 | <2.0 |
| PFDA | 0.51 | 1.10 | <0.3 | <0.3 |
| 5:3 FTCA | 0.29 | 1.40 | <0.3 | <0.3 |
| N-MeFOSAA | 0.44 | 0.44 | <0.3 | <0.3 |
| N-EtFOSAA | 0.36 | 0.44 | <0.3 | <0.3 |
| 10:2 FTS | 0.23 | 0.38 | <0.3 | <0.3 |

| | | | | |
|---|---|---|---|---|
| 7:3 FTCA | 0.15 | 0.33 | <0.3 | <0.3 |
| PFNA | <0.15 | 0.26 | <0.3 | <0.3 |
| PFOA | <0.15 | 0.22 | <0.3 | <0.3 |
| PFUnDA | <0.15 | 0.22 | <0.3 | <0.3 |
| PFDoDA | 0.17 | 0.2 | <0.3 | <0.3 |
| H4PFDS, 8:2 FTS | 0.2 | 0.42 | <0.3 | <0.3 |
| PFOSA | <0,15 | 0.31 | <0.3 | <0.3 |
| PFHxA | <0,15 | 0,0623 | <0.3 | <0.3 |
| PFTeDA | <1,5 | 0,051 | <0.3 | <0.3 |
| (6:2FTS) (H4PFOS) | <0,15 | 0,233 | <0.3 | <0.3 |
| All other 39 compounds | <LQ | <LQ | <LQ | <LQ |
| Total Fluorine (dry basis %) | 0.007 | 0.009 | 0.011 | 0.009 |
| Dry Matter (%) | 19.7 | 92.4 | 86.0 | 98.7 |

- All 50 PFAS compounds below limit of quantification (<LQ) in both biochar (SP-3) and ash/filter (SP-4)
- PFOS was the dominant compound in dried sludge at 2.10 µg/kg; all other compounds ≤1.40 µg/kg
- Total fluorine (dry basis) slightly increased from 0.009% (dried sludge) to 0.011% (biochar) — consistent with organic matrix reduction concentrating mineral fluorine, not indicating PFAS carry-through
- Concentration factor between raw sludge (19.7% DM) and dried sludge (92.4% DM) explains PFAS increase from SP-1 to SP-2 — same mass, less water

## Gaseous Phase Results

INERIS characterized the gas phase across four points: raw pyrolysis gas (SP-G1), post-combustion pre-scrubber (SP-G2), post-scrubber (SP-G3), and stack/chimney (SP-G4). This is the critical phase for understanding PFAS fate — a key knowledge gap highlighted by Sørmo et al. (2023).

- SP-G1 (raw pyrolysis gas, pre-FLOX®): 7 PFAS compounds quantified — PFBA, PFPeA, PFOA, PFHxA, 5:3 FTCA confirmed; 8:2 FTUCA and 7:3 FTCA at trace. It is observed that the amount of PFAS present in the pyrolysis gas is higher than that detected in the dried sludge. This may be attributed either to the

non-detection of certain PFAS species in the sludge matrix or to the formation of specific PFAS compounds during the pyrolysis stage.
(mass load 4.3–5.4 mg/h vs 0.923 mg/h input — see table below).

- SP-G2 (post-FLOX® combustion, pre-scrubber): all previously quantified compounds destroyed — only PFHxDA detected as a single trace (below quantification limit).
- SP-G3 (post-scrubber fumes): all PFAS <LQ.
- SP-G4 (stack/final emission): all PFAS <LQ except one trace of PFPeS (below quantification limit). TFA not detected at any point.

The FLOX® thermal oxidiser at 1000 °C effectively destroys all PFAS volatilized in the pyrolysis stage. The single stack trace (PFPeS, <LQ) is below any regulatory threshold and is consistent with findings in Sørmo et al. (2023), who noted short-chain PFAS residuals can appear in flue gas even when overall destruction exceeds 99%.

## Liquid Phase and PFAS Mass Balance

**Table 2: Kleve WWTP — PFAS Mass Balance Across All Phases**

| Stream | PFAS Load | Notes |
|---|---|---|
| Dry Sludge Input | 0.923 mg/h | Baseline 100% |
| Pyrolysis Gas (raw, SP-G1) | 4.3–5.4 mg/h | ~370–488% of input — PFAS volatilized & concentrated |
| Post-FLOX® Stack (SP-G4) | 0.00006–0.0002 mg/h | 99.99% destruction at 1000 °C |
| Biochar Product (SP-3) | 0 PFAS detected | All 50 compounds <LQ |
| Scrubber Water | <0.01 µg/L | 6:2 FTS trace Day 1 only (0.015 µg/L Day 1; <LQ Day 2) |

Scrubber water results (INERIS): all 22 PFAS <0.01 µg/L at inlet, outlet Day 2, and outlet Day 1 except for one transient trace of 6:2 FTS at 0.015 µg/L on Day 1 only (below any drinking water guideline; consistent with minor carry-through during system stabilization).

The mass balance confirms 99.99% total PFAS destruction across the combined PYREG carbonisation + FLOX® combustion process. Input load: 0.923 mg/h. Stack emission: 0.00006–0.0002 mg/h. This represents the most complete industrial-scale PFAS fate characterization for a PYREG system published to date.

## CONCLUSIONS

This study provides one of the most comprehensive full-scale assessments to date of PFAS fate and destruction during sewage sludge pyrocarbonization, covering solid, gaseous and liquid phases across the entire treatment line. Results obtained on the PYREG PX750 unit at the Kleve municipal wastewater treatment plant demonstrate that high-temperature sludge pyrocarbonization at approximately 600 °C, combined with complete thermal oxidation of pyrolysis gases at near 1000 °C, achieves near-complete PFAS destruction under real industrial operating conditions. Across the solid phase, none of the 50 targeted PFAS compounds were detected above quantification limits in the resulting biochar or in the siloxane ash fractions, despite the presence of 16 PFAS

species in the dried sludge feedstock. The observed increase in total fluorine content in the biochar relative to dried sludge reflects concentration effects associated with organic matter removal rather than PFAS persistence, confirming effective transfer and degradation of organic fluorinated compounds. Gas-phase investigations represent a key contribution of this work. While several PFAS species were detected in the raw pyrolysis gas, indicating volatilization during the carbonization stage, high-temperature FLOX® thermal oxidation resulted in the effective destruction of all quantified PFAS, with only a single compound detected sporadically below quantification limits after oxidation. Final stack emissions and post-scrubber fumes showed PFAS concentrations consistently below detection limits. The resulting mass balance confirms an overall PFAS destruction efficiency of approximately 99.99 %, in line with, and extending, previous pilot- and full-scale observations reported in the literature. Liquid phase analyses further support the robustness of the process. Scrubber effluents were analysed in accordance with the French regulatory framework for urban wastewater, covering the 22 PFAS listed in the national monitoring decree, with additional inclusion of trifluoroacetic acid (TFA). No systematic PFAS transfer to the liquid phase was observed, confirming that gas-phase oxidation effectively prevents redistribution of PFAS into secondary waste streams. Beyond contaminant removal, the process produces a PFAS-free biochar suitable for safe reuse, supporting nutrient recycling while contributing to long-term carbon sequestration.

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