Municipal Biosolids (Sludge) PFAS Treatment Literature

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
March 5, 2024	Fate of perfluoroalkyl and polyfluoroalkyl substances (PFAS) through two full-scale wastewater sludge incinerators	Lloyd J. Winchell; Martha J. M. Wells; John J. Ross; Farokh Kakar; Ali Teymouri; Dana J. Gonzalez; Ky Dangtran; Scott M. Bessler; Shane Carlson; Xavier Fonoll Almansa; John W. Norton Jr; Katherine Y. Bell	Water Environment Research	Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are an emerging issue in wastewater treatment. High-temperature thermal processes, incineration being time-tested, offer the opportunity to destroy and change the composition of PFAS. The fate of PFAS has been documented through wastewater sludge incinerators, including a multiple hearth furnace (MHF) and a fluidized bed furnace (FBF). The dewatered wastewater sludge feedstock averaged 247- and 1280-µmol targeted PFAS per sample run in MHF and FBF feed, respectively. Stack emissions (reportable for all targeted PFAS from MHF only) averaged 5% of that value with shorter alkyl chain compounds comprising the majority of the targeted PFAS. Wet scrubber water streams accumulated nonpolar fluorinated organics from the furnace exhaust with an average of 0.740- and 0.114-mol F^- per sample run, for the MHF and FBF, respectively. Simple alkane PFAS measured at the stack represented 0.5%–4.5% of the total estimated facility greenhouse gas emissions.	https://doi.org/10.1002/wer.11009	Sludge; Biosolids; PFAS Fate and Transport;sludge; evaluation; PFAS Transformation; Sludge Incineration; Stack Emissions
November 7, 2023	Treatment of poly- and perfluoroalkyl substances in U.S. full-scale water treatment systems	Timothy D. Appleman, Christopher P. Higgins, Oscar Quñones, Brett J. Vanderford, Chad Kolstad, Janie C. Zeigler-Holady, Eric R.V. Dickenson	Water Research	The near ubiquitous presence of poly- and perfluoroalkyl substances (PFASs) in humans has raised concerns about potential human health effects from these chemicals, some of which are both extremely persistent and bioaccumulative. Because some of these chem- icals are highly water soluble, one major pathway for human exposure is the consumption of contaminated drinking water. This study measured concentrations of PFASs in 18 raw drinking water sources and 2 treated wastewater effluents and evaluated 15 full-scale treatment systems for the attenuation of PFASs in water treatment utilities throughout the U.S. A liquid-chromatography tandem mass-spectrometry method was used to enable measurement of a suite of 23 PFASs, including perfluorocarboxylic acids (PFCAs) and per- fluorosulfonic acids (PFSAs). Despite the differences in reporting levels, the PFASs that were detected in >70% of the source water samples (n 1⁄4 39) included PFSAs, per- fluorobutane sulfonic acid (74%), perfluorohexane sulfonic acid (79%), and perfluorooctane sulfonic acid (84%), and PFCAs, perfluoropentanoic acid (74%), perfluorohexanoic acid (79%), perfluoroheptanoic acid (74%), and perfluorooctanoic acid (74%). More importantly, water treatment techniques such as ferric or alum coagulation, granular/micro-/ultra- filtration, aeration, oxidation (i.e., permanganate, ultraviolet/hydrogen peroxide), and disinfection (i.e., ozonation, chlorine dioxide, chlorination, and chloramination) were mostly ineffective in removing PFASs. However, anion exchange and granular activated carbon treatment preferably removed longer-chain PFASs and the PFSAs compared to the PFCAs, and reverse osmosis demonstrated significant removal for all the PFASs, including the smallest PFAS, perfluorobutanoic acid.	https://www.sciencedirect.com/science/article/pii/S0043135413008932?via%3Dihub	Drinking Water Treatment; Drinking Water Treatment Residuals; Sludge; PFAS Fate and Transport; PFAS adsorption; Granulated Activiated Carbon; Anion Exchange Resin
November 3, 2023	Per- and polyfluoroalkyl substances (PFAS) in final treated solids (Biosolids) from 190 Michigan wastewater treatment plants	Garrett W. Link, Donald M. Reeves, Daniel P. Cassidy, Ethan S. Coffin	Journal of Hazardous Materials Letters	Trends in concentration, distribution, and variability of per- and polyfluoroalkyl substances (PFAS) in biosolids are characterized using an extensive dataset of 350 samples from 190 wastewater treatment plants (WWTPs) across Michigan. All samples are comprised of final treated solids generated at the end of the wastewater treatment process. Concentrations of both individual and Σ24 PFAS are lognormally distributed, with Σ24 PFAS concentrations ranging from 1—3200 ng/g and averaging 108 ±277 ng/g dry wt. PFAS with carboxyl and sulfonic functional groups comprise 29% and 71% of Σ24 PFAS concentrations, respectively, on average. Primary sample variability in concentration is associated with long-chain PFAS with higher tendency for partitioning to biosolids. Short-chain carboxylic compounds, most notably PFHxA, are responsible for secondary concentration variability. Usage of FTSA and PFBS replacements to long-chain sulfonic compounds also contributes to variance in biosolids concentrations. Sulfonamide precursor compounds as a collective group are detected at a similar frequency as PFOS and often have higher concentrations. Trends in PFAS enrichment for individual PFAS vary at least 3 orders-of-magnitude and generally increase with compound hydrophobicity; however, partitioning of PFAS onto solids in WWTPs is a complex process not easily described nor constrained using experimentally-derived partitioning coefficients.	https://www.sciencedirect.com/science/article/pii/S0304389423020186?via%3Dihub	Sludge; Biosolids; PFAS Fate and Transport; evaluation; PFAS Transformation; PFAS partitioning; Michigan
October 6, 2023	Per- and polyfluoroalkyl substances (PFAS) at the interface of biological and environmental systems	Onur Apul, Caitlin Howell, M. Dilara Hatinoglu	Biointerphases	N/A	https://pubs.aip.org/avs/bip/article/18/5/050201/2915544/Per-and-polyfluoroalkyl-substances-PFAS-at-the	N/A
September 8, 2023	Effects of drinking water treatment residual amendments to biosolids on plant uptake of per- and polyfluoroalkyl substances	Emma Broadbent, Caleb Gravesem, Youn Jeong Choi, Linda Lee, Patrick C. Wilson, Jonathan D. Judy	Journal of Environmental Quality	Drinking water treatment residuals (DWTRs), solid by-products of drinking water treatment, are dominated by calcium (Ca), iron (Fe), or aluminum (Al), depending on the coagulant used. DWTRs are often landfilled, but current research is exploring options for beneficial reuse. Previous studies have shown that Al- and Fe-rich mate- rials have potential to reduce the mobility of per- and polyfluoroalkyl substances (PFAS). Here, we investigated how amending biosolids with 5% wt/wt DWTRs affected plant bioavailable PFAS in two different simulated scenarios: (1) agricultural scenario with *Solanum lycopersicum* (tomato) grown in soil amended with an agro- nomically relevant rate of DWTR-amended biosolids (0.9% w/w, resulting in 0.045% w/w DWTR in the biosolids-amended soil) and (2) mine reclamation scenario exam- ining PFAS uptake by *Lolium perenne* (perennial ryegrass) grown in soil that received DWTR-amended biosolids amendment at a rate consistent with the mine remediation (13% w/w, resulting in 0.65% w/w DWTR in the biosolids-amended soil). Amend- ing biosolids with Ca-DWTR significantly reduced perfluorobutanoic acid (PFBA) uptake in ryegrass and perfluorohexanoic acid uptake in tomatoes, possibly due to DWTR-induced pH elevation, while Fe-DWTR amendment reduced PFBA bioac- cumulation in ryegrass. The Al-DWTR did not induce a significant reduction in accumulated PFAS compared to controls. Although the reasons for this finding are unclear, the relatively low PFAS concentrations in the biosolids and relatively high Al content in the biosolids and soil may be partially responsible.	https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20511	Sludge; Biosolids; PFAS Fate and Transport;drinking water treatment sludge; evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation

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August 21, 2023	Management of per- and polyfluoroalkyl substances (PFAS)-laden wastewater sludge in Maine: Perspectives on a wicked problem	Simin Moavenzadeh Ghaznavi, Charity Zimmerman, Molly E. Shea, Jean D. Macrae, John M. Peckenham, Caroline L. Noblet, Onur G. Apul, A. Dianne Kopec	Biointerphases	This article discusses the challenges and potential solutions for managing wastewater sludge that contains per- and polyfluoroalkyl substances (PFAS), using the experience in Maine as a guide toward addressing the issue nationally. Traditional wastewater treatment, designed to remove excess, organic waste and nutrients, does not eliminate, persistent, toxic pollutants like PFAS, instead partitioning the chemicals between discharged effluent and the remaining solids in sludge. PFAS chemistry, the molecular size, the alkyl chain length, fluorine saturation, the charge of the head group, and the composition of the surrounding matrix influence PFAS partitioning between soil and water. Land, application of sludge, incineration, and storage in a landfill are the traditional management options. Land application of Class B sludge on agricultural fields in Maine peaked in the 1990s, totaling over 2×10^6 cu yd over a 40-year period and has contaminated certain food, crops and animal forage, posing a threat to the food supply and the environment. Additional Class A EQ (Exceptional Quality) composted sludge, was also applied to Maine farmland. The state of Maine band, the land, application of wastewater sludge in August 2022, a 14% increase over 2019. Between 2019 and 2022, the sum of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) concentrations in sludge sent to the landfill ranged from 1.2 to 104.9 ng/g dw. In 2022, the landfill generated 71.6 x 10^6 liters of leachate. The concentration of sum of six PFAS in the leachate increased sixfold between 2021 and 2022, reaching 2441 ng/l. The retention of PFAS within solid-waste landfills, and the potential for long-term release of PFAS through liners into groundwater require ongoing monitoring. Thermal treatment, incineration, or paralysis can theoretically mineralize PFAS at high temperatures, yet the strong C – F bond and reactivity of fluorine require extreme temperatures for complete mineralization. Future alternatives may include interim options, such as preconditioning PFAS with nonpolar solvent prior to immobilization in landfills, removing PFA from leachate, and interrupting the cycle of PFS, moving from landfill, via leachate, to wastewater treatment, and then back to the landfill via sludge. Long-term solutions may involve destructive technologies, such as electron bean irradiation, electrochemical advanced, oxidation, or hydrothermal liquefaction. The article highlighted the needs for innovative and sustainable solutions for managing PFAS-contaminated wastewater sludge.	https://pubs.aip.org/avs/bip/article/18/4/041004/2907432/Management-of-per-and-polyfluoroalkyl-substances	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation; Maine; Long term land application
July 14, 2023	Investigation on removal of perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS), perfluorohexane sulfonate (PFHxS) using water treatment sludge and biochar	Minh Duc Nguyen, Anithadevi Kenday Sivaram, Mallavarapu Megharaj, Lawrence Webb, Sirjana Adhikari, Michael Thomas, Aravind Surapaneni, Ellen M. Moon, Nicholas A. Milne	Chemosphere	This work assessed the adsorption performance of three common PFAS compounds (PFOA, PFOS and PFHxS) on two water treatment sludges (WTS) and two biochars commercial biomass biochar and semi-pilot scale biosolids biochar). Of the two WTS samples included in this study, one was sourced from poly-aluminium chloride (PAC) and the other from alum (Al2(SO4)3). The results of experiments using a single PFAS for adsorption reinforced established trends in affinity - the shorter-chained PFHxS was less adsorbed than PFOS, and the sulphates (PFOS) were more readily adsorbed than the acid (PFOA). Interestingly, PAC WTS, showed an excellent adsorption affinity for the shorter chained PFHxS 58.8%), than the alum WTS and biosolids biochar at 22.6% and 41.74%, respectively. The results also showed that the alum WTS was less effective at adsorption than the PAC WTS despite having a larger surface area. Taken together, the results suggest that the hydrophobicity of the sorbent and the chemistry of the coagulant were critical factors for understanding PFAS adsorption on WTS, while other factors, such as the concentration of aluminium and iron in the WTS could not explain the trends seen. For the biochar samples, the surface area and hydrophobicity are believed to be the main drivers in the different performances. Adsorption from the solution containing multiple PFAS was also investigated with PAC WTS and biosolids biochar, demonstrating comparable performance on overall adsorption. However, the PAC WTS performed better with the short-chain PFHxS than the biosolids biochar. While both PAC WTS and biosolids biochar are promising candidates for adsorption, the study highlights the need to explore further the mechanisms behind PFAS adsorption, which could be a highly variable source to understand better the potential for WTS to be utilized as a PFAS adsorbent.	https://www.sciencedirect.com/science/article/pii/S004565352301679X?via%3Dihub	Drinking Water Treatment Residuals; Sludge; PFAS Fate and Transport; PFAS adsortion; Poly-aluminum chloride; PAC; Alum; hydrophobicity; biochar;
June 27, 2023	Burning questions: Current practices and critical gaps in evaluating removal of per- and polyfluoroalkyl substances (PFAS) during pyrolysis treatments of biosolids	Joshua S. Wallace, Dulan Edirisinghe, Saba Seyedi, Haley Noteboom, Micah Blate, Derya Dursun Balci, Mohammad Abu-Orf, Robert Sharp, Jeanette Brown, Diana S. Aga	Journal of Hazardous Materials Letters	Concerns surrounding potential health and environmental impacts of per- and polyfluoroalkyl substances (PFAS) are growing at tremendous rates because adverse health impacts are expected with trace-level exposures. Extreme measures are required to mitigate potential PFAS contamination and minimize exposures. Extensive PFAS use results in the release of diverse PFAS species from domestic, industrial, and municipal effluents to wastewater, which partition to biosolids throughout secondary treatment. Biosolids generated during municipal wastewater treatment are a major environmental source of PFAS due to prevailing disposal practices as fertilizers. Pyrolysis is emerging as a viable, scalable technology for PFAS removal from biosolids while retaining nutrients and generating renewable, raw materials for energy generation. Despite early successes of pyrolysis in PFAS removal, significant unknowns remain about PFAS and transformation product fates in pyrolysis products and emissions. Applicable PFAS sampling methods, analytical workflows, and removal assessments are currently limited to a subset of high-interest analytes and matrices. Further, analysis of exhaust gases, particulate matter, fly ashes, and other pyrolysis end-products remain largely unreported or limited due to cost and sampling limitations. This paper identifies critical knowledge gaps on the pyrolysis of biosolids that must be addressed to assess the effectiveness of PFAS removal during pyrolysis treatment.	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10545407/	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal

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May 22, 2023	Leaching of select per-/poly-fluoroalkyl substances, pharmaceuticals, and hormones through soils amended with composted biosolids	Ansley J. Levine, Eban Z. Bean, Francisca O. Hinz, P. Christopher Wilson, Alexander J. Reisinger	Journal of Environmental Management	The use of organic amendments to enhance soil health is increasingly being identified as a strategy to improve residential landscapes while also reducing the need for external inputs (e.g., fertilizers, irrigation). Composted biosolids are a re-purposed waste product that can be used in organic amendments to improve the overall sustainability of a municipality by enhancing residential soil carbon content while simultaneously reducing waste materials. However, the biosolids-based feedstock of these compost products has the potential to be a source of organic contaminants. We conducted a laboratory-based soil column experiment to evaluate the potential for different commercially available compost products to act as a source of emerging organic contaminants in residential landscapes. We compared two biosolids-based compost products, a manure-based compost product, and a control (no compost) treatment by irrigating soil columns for 30 days and collecting daily leachate samples to quantify leaching rates of six hormones, eight pharmaceuticals, and seven per- and polyfluoroalkyl substances (PFAS). Detection of hormones and pharmaceuticals was rare, suggesting that compost amendments are likely not a major source of these contaminants to groundwater resources. In contrast, we detected three of the seven PFAS compounds in leachate samples throughout the study. Perfluorohexanoic acid (PFHxA) was more likely to leach from biosolids-based compost treatments than other treatments ($p < 0.05$) and perfluorobutane sulfonate (PFBS) was only detected in biosolids-based treatments (although PFBS concentrations did not significantly differ among treatments). In contrast, perfluorooctanoic acid (PFOA) was commonly detected across all treatments (including controls), suggesting potential PFOA experimental contamination. Overall, these results demonstrate that commercially available composted biosolids amendments are likely not a major source of hormone and pharmaceutical contamination. The detection of PFHxA at significantly higher concentrations in biosolids treatments suggests that biosolids-based composts may act as sources of PFHxA to the environment. However, concentrations of multiple PFAS compounds found in leachate in this study were lower than concentrations found in known PFAS hotspots. Therefore, there is potential for environmental contamination from PFAS leaching from composted biosolids, but leachate concentrations are low which should be considered in risk-benefit analyses when considering whether or not to use composted biosolids as an organic amendment to enhance residential soil health.	https://www.sciencedirect.com/science/article/pii/S0301479723009738?via%3Dihub	Sludge, Biosolids, Compost; organic amendments; soil health; PFAS Fate and Transport; Compost leachate; PFAS soil leaching
April 28, 2023	The decomposition and emission factors of a wide range of PFAS in diverse, contaminated organic waste fractions undergoing dry pyrolysis	Erlend Sørmo, Gabriela Castro, Michel Hubert, Viktória Licul-Kucera, Marjorie Quintanilla, Alexandros G. Asimakopoulos, Gerard Cornelissen, Hans Peter H. Arp	Journal of Hazardous Materials	Current treatment options for organic waste contaminated with per- and polyfluoroalkyl substances (PFAS) are generally limited to incineration, composting or landfilling, all resulting in emissions. Dry pyrolysis is a promising emerging alternative to these practices, but there is uncertainty related to the fate of PFAS during this process. The present work first developed a robust method for the determination of PFAS in complex matrices, such as sewage sludge and biochar. Then, a mass balance was established for 56 different PFAS during full-scale pyrolysis (2–10 kg biochar hr-1, 500–800 °C) of sewage sludges, food waste reject, garden waste and waste timber. PFAS were found in all wastes (56–3651 ng g-1), but pyrolysis resulted in a ≥ 96.9% removal. Residual PFAS (0.1–3.4 ng g-1) were detected in biochars obtained at temperatures up to 750 °C and were dominated by long chain PFAS. Emitted PFAS loads ranged from 0.01 to 3.1 mg tonne-1 of biochar produced and were dominated by short chain PFAS. Emissions made up < 3% of total PFAS-mass in the wastes. Remaining uncertainties are mainly related to the presence of thermal degradation products in flue gas and condensation oils.	https://www.sciencedirect.com/science/article/pii/S0304389423007306	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid;
April 6, 2023	Pyrolysis — A tool in the wastewater solids handling portfolio, not a silver bullet: Benefits, drawbacks, and future directions	Patrick McNamara, Zhongzhe Liu, Lynne Moss, Daniel Zitomer	Water Environment Research	Pyrolysis is the process whereby carbonaceous materials, such as biosolids, are heated between 400 C and 900 C in the absence of oxygen. Three main prod- ucts are generated: a solid product called biochar, a py-liquid that consists of aqueous phase and non-aqueous phase liquid, and py-gas. The biochar holds value as a beneficial soil amendment and sequesters carbon. The py-liquid is potentially hazardous and needs to be dealt with (including potentially reduc- ing it on-site via catalysis or thermal oxidation). Py-gas can be used on-site for energy recovery. Pyrolysis has gained recent interest due to concern over per- and polyfluoroalkyl substances (PFAS) in biosolids. Although pyrolysis can remove PFAS from biosolids, it has been shown to produce PFAS that reside in py-liquid, and the fate in py-gas remains a knowledge gap. More research is needed to help close the PFAS and fluorine mass balance through pyrolysis influent and effluent products because pyrolysis alone does not destroy all PFAS. The moisture content of biosolids substantially affects the energy bal- ance for pyrolysis. Utilities that already produce a dried biosolids product are in a better position to install pyrolysis. Pyrolysis has both defined benefits (solids reduction, PFAS removal from biosolids, and biochar production) as well as remaining questions (the fate of PFAS in py-gas and py-liquid, mass balance on nutrients, and py-liquid handling options) that will be answered through more pilot and full-scale demonstrations. Regulations and local poli- cies (such as carbon sequestration credits) could affect pyrolysis implementa- tion. Pyrolysis should be considered as an option in the biosolids stabilization toolbox with application being based on individual circumstances of a utility (e.g., energy, moisture content of biosolids, PFAS).	https://onlinelibrary.wiley.com/doi/abs/10.1002/wer.10863	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid;

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March 17, 2023	Microbial and thermal treatment techniques for degradation of PFAS in biosolids: A focus on degradation mechanisms and pathways	Ravinder Kumar, Tewodros Kassa Dada, Anna Whelan, Patrick Cannon, Madoc Sheehan, Louise Reeves, Elsa Antunes	Journal of Hazardous Materials	N/A	https://www.sciencedirect.com/science/article/pii/S0304389423004946	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; microbial degradation; microbes; PFAS partitioning
March 6, 2023	Per- and polyfluoroalkyl substances fate and transport at a wastewater treatment plant with a collocated sewage sludge incinerator	Brannon A. Seay, Kavitha Dasu, Ian C. MacGregor, Matthew P. Austin, Robert T. Krile, Aaron J. Frank, George A. Fenton, Derik R. Heiss, Rhett J. Williamson, Stephanie Buehler	Science of the Total Environment	This study aims to understand the fate and transport of per- and polyfluoroalkyl substances (PFAS) and inorganic fluoride (IF) at an undisclosed municipal wastewater treatment plant (WWTP) operating a sewage sludge incinerator (SSI). A robust statistical analysis characterized concentrations and mass flows at all WWTP and SSI primary influents/effluents, including thermal-treatment derived airborne emissions. WWTP-level net mass flows (NMFs) of total PFAS were not statistically different from zero. SSI-level NMFs indicate that PFAS, and specifically perfluoroalkyl acids (PFAAs), are being broken down. The NMF of perfluoroalkyl sulfonic acids (PFSAs; −274 ± 34 mg/day) was statistically significant. The observed breakdown primarily occurred in the sewage sludge. However, the total PFAS destruction and removal efficiency of 51 % indicates the SSI may inadequately remove PFAS. The statistically significant IF source (NMF = 16 ± 4.2 kg/day) compared to the sink of PFAS as fluoride (NMF = −0.00036 kg/day) suggests that other fluorine-containing substances are breaking down in the SSI. WWTP PFAS mass discharges were primarily to the aquatic environment (>99 %), with <0.5 % emitted to the atmosphere/landfill. Emission rates for formerly phased-out PFOS and PFOA were compared to previously reported levels. Given the environmental persistence of these compounds, the observed decreases in PFOS and PFOA discharge rates from prior reports implies regional/local differences in emissions or possibly their accumulation elsewhere. PFAS were observed in stack gas emissions, but modestly contributed to NMFs and showed negligible contribution to ambient air concentrations observed downwind.	https://www.sciencedirect.com/science/article/pii/S0048969723009737	Sludge; Biosolids; PFAS Fate and Transport;sludge; evaluation; PFAS Transformation; Sludge Incineration; Stack Emissions
February 15, 2023	Occurrence of quantifiable and semi-quantifiable poly- and perfluoroalkyl substances in united states wastewater treatment plants	Charles E. Schaefer, Jennifer L. Hooper, Laurel E. Strom, Ibrahim Abusallout, Eric R.V. Dickenson, Kyle A. Thompson, Gayathri Ram Mohan, Dina Drennan, Ke Wu, Jennifer L. Guelfo	Water Research	Both quantifiable and semi-quantifiable poly- and perfluoroalkyl substances (PFAS) were evaluated in the influent, effluent, and biosolids of 38 wastewater treatment plants. PFAS were detected in all streams at all facilities. For the means of the sums of detected, quantifiable PFAS concentrations were 98 ±28 ng/L, 80 ±24 ng/L, and 160,000 ±46,000 ng/kg (dry weight basis) in the influent, effluent, and biosolids (respectively). In the aqueous influent and effluent streams this quantifiable PFAS mass was typically associated with perfluoroalkyl acids (PFAAs). In contrast, quantifiable PFAS in the biosolids were primarily polyfluoroalkyl substances that potentially serve as precursors to the more recalcitrant PFAAs. Results of the total oxidizable precursor (TOP) assay on select influent and effluent samples showed that semi-quantified (or, unidentified) precursors accounted for a substantial portion (21 to 88%) of the fluorine mass compared to that associated with quantified PFAS, and that this fluorine precursor mass was not appreciably transformed to perfluoroalkyl acids within the WWTPs, as influent and effluent precursor concentrations via the TOP assay were statistically identical. Evaluation of semi-quantified PFAS, consistent with results of the TOP assay, showed the presence of several classes of precursors in the influent, effluent, and biosolids; perfluorophosphonic acids (PFPAs) and luorotelomer phosphate diesters (di-PAPs) occurred in 100 and 92% of biosolid samples, respectively. Analysis of mass flows showed that, for both quantified (on a fluorine mass basis) and semi-quantified PFAS, the majority of PFAS exited WWTPs through the aqueous effluent compared to the biosolids stream. Overall, these results highlight the importance of semi-quantified PFAS precursors in WWTPs, and the need to further understand the impacts of their ultimate fate in the environment.	https://www.sciencedirect.com/science/article/pii/S0043135423001598?via%3Dihub	PFAS Fate and Transport; Influent; Effluent; Sludge; Total Oxidizable Precursor Assay; PFAS precusror; PFAS Transformation;
February 7, 2023	Underestimation of Per- and Polyfluoroalkyl Substances in Biosolids: Precursor Transformation During Conventional Treatment	Jake T. Thompson, Nicole M. Robey, Thabet M. Tolaymat, John A. Bowden, Helena M. Solo-Gabriele, Timothy G. Townsend	Environmental Science & Technology	Wastewater treatment plants generate a solid waste known as biosolids. The most common management option for biosolids is to beneficially reuse them as an agricultural amendment, but because of the risk of pathogen exposure, many regulatory bodies require pathogen reduction before biosolids reuse. Per- and polyfluoroalkyl substances (PFAS) are well documented in biosolids, but limited information is available on how biosolids treatment processes impact PFAS. Furthermore, quantification of PFAS has focused on perfluoroalkyl acids (PFAAs) which are a small fraction of thousands of PFAS known to exist. The objective of this study was to quantify 92 PFAS in biosolids collected from eight biosolids treatment facilities before and after four pathogen treatment applications: composting, heat treatment, lime treatment, and anaerobic digestion. Overall, total PFAS concentrations before and after treatment were dominated by PFAA precursor species, in particular, diPAPs which accounted for a majority of the mass of the Σ92PFAS. This differs from historic data that found PFAAs, primarily PFOS, to dominate total PFAS concentrations. Treatment options such as heat treatment and composting changed the ratio of PFAA precursors to PFAAs indicating a transformation of PFAS during treatment. This study finds that PFAA precursors are likely underrepresented by other studies and make up a larger percentage of the total PFAS concentration in biosolids than previously estimated.	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10500628/	Sludge; Biosolids; PFAS Fate and Transport; diPAP precusor; evaluation; PFAS Transformation; Biosolids Treatment;

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
January 2, 2023	The analysis of per- and polyfluoroalkyl substances in wastewater sludges and biosolids: which adsorbents should be used for the cleanup of extracts?	Ali Can Ozelcaglayan, Wayne J. Parker and Anh Le-Tuan Pham	Environmental Science: Water Research & Technology	The analysis of PFAS in wastewater treatment sludges and biosolids is an evolving practice for which a widely recognized standard method does not currently exist. While a number of analytical techniques have been reported in the literature, individual methods were found to not be broadly applicable over a range of sludge/biosolid matrices. This study critically examined the method employed to clean up biosolid extracts prior to LC-MS/MS analysis, which was determined to be crucial to obtaining acceptable chromatogram quality and recoveries of a range of PFAS and associated surrogates. When ENVI-Carb was employed alone or in combination with WAX, as described in US EPA Draft Method 1633, precipitates were formed when methanolic extracts were reconstituted with water, preventing direct analysis by LC-MS/MS. Centrifugation and filtration of reconstituted extracts to remove precipitates did not sufficiently eliminate interferences to allow PFAS quantification. The use of blends of adsorbents (ENVI-Carb, PSA, C18) with different adsorptive properties that could remove a broader range of interfering substances was evaluated. A blend consisting of 1000 mg ENVI-Carb, 500 mg PSA and 500 mg C18 was found to effectively eliminate background interference while providing an optimal trade-off between chromatogram quality and PFAS recovery. When integrated into the overall analytical method, the recoveries of PFAS were between 40% and 160% except for some precursors when six different biosolids were analyzed. The cleanup method developed in this study has the potential to facilitate the analysis of PFAS in a broad range of sludge and biosolid matrices.	https://pubs.rsc.org/en/content/articlelanding/2023/ew/d2ew00617k	Sludge; Biosolids; PFAS Fate and Transport; PFAS Test Methods; PFAS evaluation; PFAS precursor; clean-up method
December 28, 2022	Influence of microbial weathering on the partitioning of per- and polyfluoroalkyl substances (PFAS) in bisolids	Asa J. Lewis, Farshad Ebrahimi, Erica R. McKenzie, Rominder Suri and Christopher M. Sales	Environmental Science: Processes & Impacts	Per- and polyfluoroalkyl substances (PFAS) are a large group of man-made fluorinated organic chemicals that can accumulate in the environment. In water resource recovery facilities (WRRFs), some commonly detected PFAS tend to partition to and concentrate in biosolids where they can act as a source to ecological receptors and may leach to groundwater when land-applied. Although biosolids undergo some stabilization to reduce pathogens before land application, they still contain many microorganisms, contributing to the eventual decomposition of different components of the biosolids. This work demonstrates ways in which microbial weathering can influence biosolids decomposition, degrade PFAS, and impact PFAS partitioning in small-scale, controlled laboratory experiments. In the microbial weathering experiments, compound-specific PFAS biosolids–water partitioning coefficients (Kd) were demonstrated to decrease, on average, 0.4 logs over the course of the 91 day study, with the most rapid changes occurring during the first 10 days. Additionally, the highest rates of lipid, protein, and organic matter removal occurred during the same time. Among the evaluated independent variables, statistical analyses demonstrated that the most significant solids characteristics that impacted PFAS partitioning were organic matter, proteins, lipids, and molecular weight of organics. A multiple linear regression model was built to predict PFAS partitioning behavior in biosolids based on solid characteristics of the biosolids and PFAS characteristics with a R2 value of 0.7391 when plotting predicted and measured log Kd. The findings from this work reveal that microbial weathering can play a significant role in the eventual fate and transport of PFAS and their precursors from biosolids.	https://pubs.rsc.org/en/content/articlelanding/2023/em/d2em00350c	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; microbial degradation; microbes; PFAS partitioning
December 16, 2022	Pyrolysis transports, and transforms, PFAS from biosolids to py-liquid	Patrick McNamara, Melvin S. Samuel, Sandeep Sathyamoorthy, Lynne Moss, Danny Valtierra, Hugo Cortes Lopez, Nick Nigro, Stephen Somerville, Zhongzhe Liu	Environmental Science: Water Research & Technology	Per- and poly-fluoroalkyl substances (PFAS) in wastewater solids have resulted in bans on land application of biosolids, causing utilities to explore thermal treatment options. Pyrolysis is a thermal treatment process that converts wastewater solids to biochar, py-liquid (i.e., aqueous phase liquid and non-aqueous phase liquid), and py-gas. Research on the impact of pyrolysis on PFAS in biosolids has yielded mixed results, and no research has investigated if PFAS are present in the py-liquid. The goals of this research were to determine if pyrolysis releases PFAS with the effluent py-liquid and to distinguish “removal” from “transformation” of PFAS. Triplicate batch pyrolysis experiments were performed at 500 °C, 650 °C, and 800 °C. Targeted PFAS were analyzed in biosolids, biochar, and py-liquid via LC-MS/MS, and PFAS precursor compounds were measured in the biosolids and biochar using the total oxidizable precursor assay. Pyrolysis removed all targeted PFAS from resulting biochars, with the one exception of perfluorobutanoic acid (PFBA) being present slightly above detection limit in one of the 800 °C biochar samples. PFAS precursor compounds were not detected in five of the nine biochar samples, and the other four biochar samples had only perfluoropentanoic acid (PFPeA) detected slightly above detection limit. Overall, pyrolysis removed >99% of targeted PFAS and PFAS precursor compounds from the solid phase. Interestingly, the mass of N-ethyl perfluorooctane sulfonamidoethanol (NEtFOSE), and N-methyl perfluorooctane sulfonamidoethanol (NMeFOSE) increased by over two orders of magnitude in the effluent py-liquid compared to the influent biosolids. This phenomenon occurred at all three temperatures tested. Similarly, the mass of PFBA also substantially increased following pyrolysis due either to the thermal breakdown of higher chain PFAS, the transformation of PFBA precursor compounds, or a combination of both. These key findings illuminate that pyrolysis of biosolids can cause transformation reactions that lead to specific PFAS in the effluent py-liquid found at higher levels than in the influent biosolids. Overall, this research indicates that pyrolysis could be employed to remove PFAS from biosolids to generate a value-added biochar product for soil amendment benefits, but py-liquid that contains PFAS could also be generated.	https://pubs.rsc.org/en/content/articlelanding/2023/ew/d2ew00677d	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid;

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
December 8, 2022	Recent advances on PFAS degradation via thermal and nonthermal methods	Sanny Verma, Tae Lee, Endalkachew Sahle-Demessie, Mohamed Ateia, Mallikarjuna N. Nadagouda	Chemical Engineering Journal Advances	Per- and polyfluoroalkyl substances (PFAS) are a set of synthetic chemicals which contain several carbon-fluorine (C–F) bonds and have been in production for the past eight decades. PFAS have been used in several industrial and consumer products including nonstick pans, food packaging, firefighting foams, and carpeting. PFAS require proper investigations worldwide due to their omnipresence in the biotic environment and the resulting pollution to drinking water sources. These harmful chemicals have been associated with adverse health effects such as liver damage, cancer, low fertility, hormone subjugation, and thyroid illness. In addition, these fluorinated com pounds show high chemical, thermal, biological, hydrolytic, photochemical, and oxidative stability. Therefore, effective treatment processes are required for the removal and degradation of PFAS from wastewater, drinking water, and groundwater. Previous review papers have provided excellent summaries on PFAS treatment tech nologies, but the focus has been on the elimination efficiency without providing mechanistic understanding of removal/degradation pathways. The present review summarizes a comprehensive examination of various ther mal and non thermal PFAS destruction technologies. It includes sonochemical/ultrasound degradation, micro wave hydrothermal treatment, subcritical or supercritical treatment, electrical discharge plasma technology, thermal destruction methods/incinerations, low/high-temperature thermal desorption process, vapor energy generator (VEG) technology and mechanochemical destruction. The background, degradation mechanisms/pathways, and advances of each remediation process are discussed in detail in this review.	https://doi.org/10.1016/j.ceja.2022.100421	PFAS Treatment; waste; Thermal Treatment; electrochemical oxidation; gasification, supercrital water oxidation, pyrolysis;
December 8, 2022	Recent advances on PFAS degradation via thermal and nonthermal methods	Sanny Verma, Tae Lee, Endalkachew Sahle-Demessie, Mohamed Ateia, Mallikarjuna N. Nadagouda	Chemical Engineering Journal Advances	Per- and polyfluoroalkyl substances (PFAS) are a set of synthetic chemicals which contain several carbon-fluorine (C–F) bonds and have been in production for the past eight decades. PFAS have been used in several industrial and consumer products including nonstick pans, food packaging, firefighting foams, and carpeting. PFAS require proper investigations worldwide due to their omnipresence in the biotic environment and the resulting pollution to drinking water sources. These harmful chemicals have been associated with adverse health effects such as liver damage, cancer, low fertility, hormone subjugation, and thyroid illness. In addition, these fluorinated compounds show high chemical, thermal, biological, hydrolytic, photochemical, and oxidative stability. Therefore,effective treatment processes are required for the removal and degradation of PFAS from wastewater, drinking water, and groundwater. Previous review papers have provided excellent summaries on PFAS treatment technologies, but the focus has been on the elimination efficiency without providing mechanistic understanding of removal/degradation pathways. The present review summarizes a comprehensive examination of various thermal and non-thermal PFAS destruction technologies. It includes sonochemical/ultrasound degradation, microwave hydrothermal treatment, subcritical or supercritical treatment, electrical discharge plasma technology, thermal destruction methods/incinerations, low/high-temperature thermal desorption process, vapor energy generator (VEG) technology and mechanochemical destruction. The background, degradation mechanisms/pathways, and advances of each remediation process are discussed in detail in this review.	https://www.sciencedirect.com/science/article/pii/S2666821122001818?via%3Dihub	PFAS, Thermal degradation, Nonthermal degradation, Incineration, Mineralization
October 29, 2022	Treatment technologies for removal of per- and polyfluoroalkyl substances (PFAS) in biosolids	Anushka Garg, Nagaraj P. Shetti, Soumen Basu, Mallikarjuna N. Nadagouda, Tejraj M. Aminabhavi	Chemical Engineering Journal	PFAS (per- and polyfluoroalkyl substances) possess hydrophobic and hydrophilic characteristics, recalcitrant nature due to a strong C-F bond, and have the potential to endure adverse environmental situations and greater surface activity. Biosolids are the side-resultant in the sludge treatment process, which are primarily applied as soil conditioners. These PFAS have been detected at an abnormal level in biosolids and through various routes retained in the human and animal systems. However, for PFAS, in-depth consideration of physical and chemical properties and exposure pathways is still limited, ultimately curbing the development of new technologies which pave the trails for PFAS destruction. Several attempts have been carried out using the biological approach, and hydrolytic methods, but the carbon–fluorine bond being resistant to these approaches limits them. Therefore, impactful end-of-life technologies are required for PFAS remediation in biosolids. The current review provides new insights into PFAS destruction technologies. Different emerging PFAS destruction technologies such as incineration, hydrothermal liquefaction, pyrolysis, thermal hydrolysis, supercritical water oxidation, and several other processes, their latest advancements and limitations have been discussed in detail in this current study. Classification of PFAS, exposure of PFAS to the environment and human exposure, ways in which humans can avoid PFAS, and different detection techniques for PFAS analysis along with their merits and demerits have been broadly discussed in this review. The mechanism of PFAS degradation during thermal processes has also been covered.	https://doi.org/10.1016/j.cej.2022.139964	PFAS Treatment; waste; electrochemical oxidation; gasification, supercrital water oxidation, pyrolysis; sludge; PFAS evaluation
October 25, 2022	High-Temperature Pyrolysis for Elimination of Per- and Polyfluoroalkyl Substances (PFAS) from Biosolids	Hanieh Bamdad, Sadegh Papari, Emma Moreside, Franco Berruti	Processes	Biosolids generated as byproducts of wastewater treatment processes are widely used as fertilizer supplements to improve soil condition and ultimately agricultural products yields and quality. However, biosolids may contain toxic compounds, i.e., per- and polyfluoroalkyl substances (PFAS), which can end up in soils, groundwater, and surface water, causing adverse environmental and health effects. The purpose of this study was to investigate the application of High-Temperature Pyrolysis (HTP) treatment for biosolids management, and its efficacy in eliminating PFAS from the solid fraction. Biosolid samples were pyrolyzed at two different temperatures, 500 and 700 deg C, in a continuous bench-scale pyrolysis unit. The major finding is that the treatment process at higher pyrolysis temperatures can remarkably reduce or eliminate the level of PFAS (by ~97–100 wt%) in the resulting biochar samples.	https://www.mdpi.com/2227-9717/10/11/2187	PFAS Treatment; waste; Thermal Treatment; thermal treatment; sludge; biosolids; pyrolysis; py-gas

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
September 20, 2022	Review of influence of critical operation conditions on by-product/intermediate formation during thermal destruction of PFAS in solid/biosolids	Jianhua Zhang, Li Gao, David Bergmann, Tamara Bulatovic, Aravind Surapaneni, Stephen Gray	Science of the Total Environment	Poly- and perfluoroalkyl substances (PFAS) are a large group of synthetic organofluorine compounds. Over 4700 PFAS compounds have been produced and used in our daily life since the 1940s. PFAS have received considerable interest because of their toxicity, environmental persistence, bioaccumulation and wide existence in the environment. Various treatment methods have been developed to overcome these issues. Thermal treatment such as combustion and pyrol ysis/gasification have been employed to treat PFAS contaminated solids and soils. However, short-chain PFAS and/or volatile organic fluorine is produced and emitted via exhaust gas during the thermal treatment. Combustion can achieve complete mineralisation of PFAS at large scale operation using temperatures >1000 °C. Pyrolysis has been used in treatment of biosolids and has demonstrated that it could remove PFAS completely from the generated biochar by evaporation and degradation. Although pyrolysis partially degrades PFAS to short-chain fluorine containing or ganics in the syngas, it could not efficiently mineralise PFAS. Combustion of PFAS containing syngas at 1000 °C can achieve complete mineralisation of PFAS. Furthermore, the by-product of mineralisation, HF, should also be moni tored due to its low regulated atmospheric discharge values. Alkali scrubbing is normally required to lower the HF con centration in the exhaust gas to acceptable discharge concentrations.	https://doi.org/10.1016/j.scitotenv.2022.158796	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid;
July 4, 2022	Incorporating hydrothermal liquefaction into wastewater treatment – Part I: Process optimization for energy recovery and evaluation of product distribution	Huan Liu, Ibrahim Alper Basar, Nathalie Lyczko, Ange Nzihou, Cigdem Eskicioglu	Chemical Engineering Journal	The treatment of significant amounts of municipal sewage sludge requires novel and efficient technologies. This study evaluated hydrothermal liquefaction as a means to sustainably convert sludge waste into a renewable energy source – biocrude, which can mitigate both environmental and energy-related challenges. Response surface methodology was employed to investigate the effects of reaction temperature (290–360 °C) and residence time (0–30 min) on product yield and biocrude quality. Both the highest and the lowest reaction temperature or residence time had negative effects on biocrude yield and energy recovery (ER), while high reaction severities improved biocrude quality. Under optimized conditions (332 °C for 16.9 min), biocrude yield (48.9%, dry ash-free) and ER (70.8%) were maximized. Biocrude composition followed the order of N-heterocycles > O-heterocycles > hydrocarbons, while nitrogenous compounds reduced, and hydrocarbons increased with reaction temperature. More distillable fractions in biocrude were also produced at higher reaction severities. The possible reaction pathways of biocrude formation were discussed and updated to include catalytic effects on inherent metals and Brønsted (acidic and basic) sites. The high content of O (7.8–13.1%), N (4.4–4.9%), and TAN (48.6–63.6 mg KOH/g) suggested the necessity of biocrude upgrading. Separating and recycling trace metals (e.g., 497–656 mg/kg Fe) from biocrude are necessary to relieve upgrading challenges. C, N, and P were mostly distributed into HTL biocrude, aqueous, and hydrochar, respectively, allowing their recovery. Most metals were concentrated in hydrochar. The results contribute to the advancement of the state of the art in biorefinery, which will guide the design of full-scale HTL sludge treatment systems combining resource recovery.	https://www.sciencedirect.com/science/article/abs/pii/S1385894722033253	Sludge; Biosolids; Hydrothermal Liquefaction (HTL); biofuel; biocrude oil; PFAS minerialization;
May 24, 2022	Efficient workflow for suspect screening analysis to characterize novel and legacy per- and polyfluoroalkyl substances (PFAS) in biosolids	Rebecca A. Dickman, Diana S. Aga	Analyticial and Bioanalytical Chemistry	Land application of treated sewage sludge (also known as biosolids) is considered a sustainable route of disposal because it reduces waste loading into landfills while improving soil health. However, this waste management practice can introduce contaminants from biosolids, such as per- and polyfluoroalkyl substances (PFAS), into the environment. PFAS have been observed to be taken up by plants, accumulate in humans and animals, and have been linked to various negative health effects. There is limited information on the nature and amounts of PFAS introduced from biosolids that have undergone dif- ferent treatment processes. Therefore, this study developed analytical techniques to improve the characterization of PFAS in complex biosolid samples. Different clean-up techniques were evaluated and applied to waste-activated sludge (WAS) and lime-stabilized primary solids (PS) prior to targeted analysis and suspect screening of biosolid samples. Using liquid chromatography with high-resolution mass spectrometry, a workflow was developed to achieve parallel quantitative targeted analysis and qualitative suspect screening. This study found that concentrations of individual PFAS (27 targeted analytes) can range from 0.6 to 84.6 ng/g in WAS (average total PFAS = 241.4 ng/g) and from 1.6 to 33.8 ng/g in PS (average total PFAS = 72.1 ng/g). The suspect screening workflow identified seven additional PFAS in the biosolid samples, five of which have not been previously reported in environmental samples. Some of the newly identified compounds are a short-chain polyfluorinated carboxylate (a PFOS replacement), a diphosphate ester (a PFOA precursor), a possible transformation product of carboxylate PFAS, and an imidohydrazide which contains a sulfonate and benzene ring.	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9142425/	Sludge; Biosolids; PFAS Fate and Transport; diPAP precusor; evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
May 21, 2022	Stabilization of per- and polyfluoroalkyl substances (PFAS) in sewage sludge using different sorbents	Weilan Zhang, Tao Jiang, Yanna Liang	Journal of Hazardous Materials Advances	Sewage sludge is known to contain a wide range of per- and polyfluoroalkyl substances (PFAS). To test the feasibility of stabilizing PFAS in sludge, we spiked two known amounts of six perfluorinated carboxylic acids (PFCAs, C6 – C11), three perfluoroalkane sulfonic acids (PFSAs, C4 – C8), and GenX to the sludge and amended it with biochar, granular activated carbon (GAC), or one RemBind® product (100 or 100X) at different doses. Our results showed that RemBind® 100X had the best stabilization performance, followed by GAC and RemBind® 100. Biochar had little effect on decreasing leaching of PFAS. Compared to control sludge without any sorbents at an initial PFAS concentration of 30 μg/kg, the treatment by RemBind® 100X at 2 wt.% after 35 days led to decrease of a ΣPFAS leaching by 89% in the water and 85% in the SPLP leachates. At 300 μg/kg, a similar trend was observed as well. RemBind® 100X, GAC, and RemBind® 100 at a dose of 1 wt.% stabilized PFAS and resulted in significantly lower leachable ΣPFAS than that at a dose of 0.1 wt.%, indicating the dose-effect of sorbents on PFAS stabilization in sludge. During the experimental duration of 115 days, the leachable PFAS gradually increased with time for those with GAC but fluctuated in the water leachate of the sludge with RemBind® 100X, implying a dynamic adsorption/desorption process and potential degradation of PFAS precursors occurring during the incubation. Overall, this study demonstrated the positive effect of sorbent addition toward decreasing PFAS leaching by water and acidic water. The fact that the stabilized PFAS can be extracted well by basic methanol, although this may happen rarely in reality, raises the question of remediation end point, which deserves to be further investigated.	https://www.sciencedirect.com/science/article/pii/S2772416622000456	Sludge; biosolids, biochar, stabilization; incubation; Granulated activated carbon
April 1, 2022	Occurrent of per- and polyfluoroalkyl substances in water: a review	Yifei Wang, Juhee Kim, Ching-Hua Huang, Gary L. Hawkins, Ke Li, Yongsheng Chen, Quingguo Huang	Environmental Science: Water Research & Technology	Per- and polyfluoroalkyl substances (PFASs) have drawn increasing concern due to their widespread pres- ence and persistence in the environment. In contrast, methods and manuals have been developed only re- cently to provide recommended analysis procedures for a growing list of selected PFASs, with more quality assurance and quality control (QA/QC) measures incorporated to ensure data robustness. This review ex- amined studies on the environmental occurrence of PFASs in different water systems in the United States (US) along with similar studies in the other countries. The review has thus revealed a few patterns regarding the environmental occurrence of PFASs having different molecular features, the impact of possible up- stream PFAS sources, and the effects of water treatment facilities. Further research is needed to analyze a wider array of PFASs, particularly those playing roles in PFAS degradation pathways. The review also indi- cates a need for technologies capable of destructing PFASs in addition to those separation processes cur- rently implemented at water treatment facilities to mitigate the environmental presence of PFASs.	https://pubs.rsc.org/en/content/articlelanding/2022/ew/d1ew00851j#!divRelatedContent&articles	Drinking Water Treatment; Drinking Water Treatment Residuals; Sludge; PFAS Fate and Transport; PFAS adsortion; Granulated Activiated Carbon; Anion Exchange Resin
March 28, 2022	High-temperature technology survey and comparison among incineration, pyrolysis, and gasification systems for water resource recovery facilities	Lloyd J. Winchell, John J. Ross, Dominic A. Brose, Thaís B. Pluth, Xavier Fonoll, John W. Norton Jr., Katherine Y. Bell	Water Environment Research	Solids from wastewater treatment undergo processing to reduce mass, minimize pathogens, and condition the products for specific end uses. However, costs and contaminant concerns (e.g., per- and polyfluoroalkyl substances [PFAS]) challenge traditional landfill and land application practices. Incineration can overcome these issues but has become complicated due to evolving emissions regulations, and it suffers from poor public perception. These circumstances are driving the re-emergence of pyrolysis and gasification technologies. A survey of suppliers was conducted to document differences with technologies. Both offer advantages over incineration with tailored production of a carbon-rich solid, currently less stringent air emission requirements, and lower flue gas flows requiring treatment. However, incineration more simply combines drying and thermal processing into one reactor. Equipment costs provided favor pyrolysis and gasification at lower capacities but converge with incineration at higher capacities. Long-term operational experience will confirm technology competitiveness and elucidate whether pyrolysis and gasification warrant widespread adoption.	https://doi.org/10.1002/wer.10715	PFAS Treatment; waste; Thermal Treatment; thermal treatment; sludge; biosolids gasification, , pyrolysis; py-gas
March 4, 2022	Pyrolysis and gasification at water resource recovery facilities: Status of the industry	Lloyd J. Winchell, John J. Ross, Dominic A. Brose, Thaís B. Pluth, Xavier Fonoll, John W. Norton Jr, Katherine Y. Bell	Water Environment Research	Wastewater treatment generates solids requiring subsequent processing. Costs and contaminant concerns (e.g., per- and polyfluoroalkyl substances [PFAS]) are challenging widely used landfilling and land application practices. These circumstances are partly driving the re-emergence of pyrolysis and gasification technologies along with beneficial reuse prospects of the char solid residual. Previously, technologies experienced operational challenges leading to revised configurations, such as directly coupling a thermal oxidizer to the reactor to destroy tar forming compounds. This paper provides an overview of pyrolysis and gasification technologies, characteristics of the char product, air emission considerations, and potential fate of PFAS and other pollutants through the systems. Results from a survey of viable suppliers illustrate differences in commercially available options. Additional research is required to validate performance over the long-term operation and confirm contaminant fate, which will help determine whether resurging interest in pyrolysis and gasification warrants widespread adoption.	https://doi.org/10.1002/wer.10701	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid; thermal treatment technologies; landfill

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
February 11, 2022	Pyrolysis Processing of PFAS-Impacted Biosolids, a Pilot Study	Eben D. Thoma, Robert S. Wright, Ingrid George, Max Krause, Dario Presezzi, Valentino Villa, William Preston, Parik Deshmukh, Phil Kauppi, Peter G. Zemek	Journal of the Air & Waste Management Association	Concentrations of per- and poly-fluoroalkyl substances (PFAS) present in wastewater treatment biosolids is a growing concern. Pyrolysis is a thermal treatment technology for biosolids that can produce a useful biochar product with reduced levels of PFAS and other contaminants. In August 2020, a limited-scope study investigated target PFAS removal of a commercial pyrolysis system processing biosolids with analysis of 41 target PFAS compounds in biosolids and biochar performed by two independent laboratories. The concentrations of 21 detected target compounds in the input biosolids ranged between approximately 2 µg/kg and 85 µg/kg. No PFAS compounds were detected in the biochar. The PFAS concentrations in the biochar were assumed to equal the compounds' minimum detection limits (MDLs). The pyrolysis system's target PFAS removal efficiencies (REs) were estimated to range between >81.3% and >99.9% (mean = >97.4%) with the lowest REs being associated with the lowest detected PFAS concentrations and the highest MDLs. No information on non-target PFAS compounds in influent or effluent media or products of incomplete combustion were considered. Select gaseous emissions were measured by Fourier transform infrared spectroscopy and gas chromatography time-of-flight mass spectrometry to provide additional information on air emissions after process controls. This limited-scope study indicated that additional research to further understand this process is warranted.	https://www.tandfonline.com/doi/full/10.1080/10962247.2021.2009935	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal
January 5, 2022	Developing innovative treatment technologies for PFAS-containing wastes	Chelsea Berg, Brian Crone, Brian Gullett, Mark Higuchi, Max J. Krause, Paul M. Lemieux, Todd Martin, Erin P. Shields, Ed Struble, Eben Thoma, and Andrew Whitehill	Journal of the Air & Waste Management Association	The release of persistent per- and polyfluoroalkyl substances (PFAS) into the environment is a major concern for the United States Environmental Protection Agency (U.S. EPA). To complement its ongoing research efforts addressing PFAS contamination, the U.S. EPA's Office of Research and Development (ORD) commissioned the PFAS Innovative Treatment Team (PITT) to provide new perspectives on treatment and disposal of high priority PFAS-containing wastes. During its six-month tenure, the team was charged with identifying and developing promising solutions to destroy PFAS. The PITT examined emerging technologies for PFAS waste treatment and selected four technologies for further investigation. These technologies included mechanochemical treatment, electrochemical oxidation, gasification and pyrolysis, and supercritical water oxidation. This paper highlights these four technologies and discusses their prospects and the development needed before potentially becoming available solutions to address PFAS-contaminated waste.	https://www.tandfonline.com/doi/full/10.1080/10962247.2021.2000903	PFAS Treatment; waste; electrochemical oxidation; gasification, supercritical water oxidation, pyrolysis;
November 23, 2021	Supercritical Water Oxidation as an Innovative Technology for PFAS Destruction	Max J. Krause, Eben Thoma, Endalkachew Sahle-Damesessie, Brian Crone, Andrew Whitehill, Erin Shields, and Brian Gullett	ASCE Journal of Environmental Engineering	Water above 374°C and 22.1 MPa becomes supercritical, a special state where organic solubility increases and oxidation processes are accelerated. Supercritical water oxidation (SCWO) has been previously shown to destroy hazardous substances such as halogenated compounds. Three separate providers of SCWO technology were contracted to test the efficacy of SCWO systems to reduce per- and poly-fluoroalkyl substances (PFAS) concentrations from solutions of dilute aqueous film-forming foam (AFFF). The findings of all three demonstration studies showed a greater than 99% reduction of the total PFAS identified in a targeted compound analysis, including perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA). PFOS was reduced from 26.2 mg/L to 240 ug/L, 30.4 mg/L to 0.310 ug/L, and 190 mg/L to 8.57 ug/L, from the Aquarden, Battelle, and 374Water demonstrations, respectively. Similarly, PFOA was reduced from 930 to 0.14 ug/L, 883 to 0.102 ug/L, and 3,100 ug/L to nondetect in the three evaluations. Additionally, the chemical oxygen demand of the dilute AFFF was shown to reduce from 4,750 to 5.17 mg/L after treatment, indicating significant organic compound destruction. In one demonstration, a mass balance of the influent and effluent found that the targeted compounds accounted for only 27% of the generated fluoride, suggesting that more PFAS were destroyed than measured and emphasizing the limitations of targeted analysis alone. As a destructive technology, SCWO may be an alternative to incineration and could be a permanent solution for PFAS-laden wastewaters rather than disposal by injection into a deep well or landfilling. Additional investigation of reaction byproducts remains to be conducted for a complete assessment of SCWO's potential as a safe and effective PFAS treatment technology.	https://doi.org/10.1061/(ASCE)EE.1943-7870.0001957	PFAS Treatment; waste; Thermal Treatment; oxidation; supercritical water oxidation, wastewater; influent; effluent
May 12, 2021	Distribution and fate of per- and polyfluoroalkyl substances (PFAS) in wastewater treatment facilities	Elham Tavasoli, Jenna L. Luek, James P. Malley Jr., and Paula J. Mouser		Anthropogenic compounds known as per- and polyfluoroalkyl substances (PFAS) represent a major class of contaminants of emerging concern composed of nearly 5000 chemicals. Many PFAS are persistent, bioaccumulative and toxic, and their widespread use makes their environmental distribution a growing concern. Wastewater treatment facilities (WWTFs) are a conduit of PFAS to the environment, integrating common household products from municipal sewage, industrial wastewater sources, septic materials, and firefighting wastewaters in effluent and sludge. This study investigated the distribution and fate of twenty-four PFAS within six New Hampshire municipal WWTFs applying a range of biological and disinfection unit processes. PFAS quantification was conducted using two approaches: (1) liquid chromatography with tandem mass spectrometry (LC-MS/MS) of 24 known compounds and (2) a total oxidizable precursor assay (TOP assay) followed by LC-MS/MS to determine the total oxidizable PFAS concentration. Of the 24 PFAS analyzed, up to 7 and 12 constituents were detected in influent and effluent of WWTFs, respectively, with concentrations ranging from 30 to 128 ng L1 in March. Effluent SPFAS concentration increased during July, with concentrations between 70 and 198 ng L1 for the same detected constituents. Short-chain PFAS were dominant in both influent and effluent, while long- chain compounds dominated in WWTF sludge. The increase in terminal end-products after oxidation by the TOP assay indicates the presence of unquantified PFAS precursors in both influent and effluent. A significantly lower proportion of oxidizable PFAS precursors were detected in July influent and effluent relative to March, indicating a possible role of season or temperature on microbial transformation of these compounds prior to reaching WWTFs and during treatment. These results provide new insight into PFAS distribution and fate during two seasons in New England municipal WWTFs.	https://pubs.rsc.org/en/content/articlelanding/2021/EM/D1EM00032B	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; New Hampshire; total oxidizable precursor assay PFAS partitioning

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
December 16, 2020	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	Sazal Kundu, Savankumar Patel, Pobitra Halder, Tejas Patel, Mojtaba Hedayati Marzbali, Biplob Kumar Pramanik, Jorge Paz-Ferreiro, Cícero Célio de Figueiredo, David Bergmann, Aravind Surapaneni, Mallavarapu Megharaj and Kalpit Shah	Environmental Science: Water Research & Technology	This study aims to (a) investigate the performance of a semi-pilot fluidised bed pyrolysis unit in converting biosolids into biochar, (b) examine the ability of the pyrolysis–combustion integrated process to destruct PFASs present in biosolids and (c) study the application of biosolids derived biochar for removing PFASs from contaminated water. The semi-pilot fluidised bed pyrolysis unit demonstrated stable temperature and oxygen profiles in the reactor. The yield of biochar was found to be 36–45% at studied temperatures (500–600 °C). The produced biosolids derived biochar samples, due to their lower H/C and O/C ratio, were found to be extremely stable with an expected long (millennia) residence time in soil. It was concluded that >90% removal of perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA) from biosolids derived biochar could be achieved in the pyrolysis–combustion integrated process. The biosolids derived biochar demonstrated >80% adsorption of long-chain PFASs and 19–27% adsorption of short-chain PFASs from PFAS contaminated water.	https://pubs.rsc.org/en/content/articlelanding/2021/EW/D0EW00763C	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal
November 15, 2020	Per- and polyfluoroalkyl substances thermal destruction at water resource recovery facilities: A state of the science review	Lloyd J.Winchell, John J. Ross, Martha J. M.Wells, Xavier Fonoll, John W. Norton Jr, Katherine Y. Bell	Water Environment Research	Per- and polyfluoroalkyl substances (PFAS) are a recalcitrant group of chemicals and can be found throughout the environment. They often collect in wastewater systems with virtually no degradation prior to environmental discharge. Some PFAS partitions to solids captured in wastewater treatment which require further processing. Of all the commonly applied solids treatment technologies, incineration offers the only possibility to completely destroy PFAS. Little is known about the fate of PFAS through incineration, in particular, for the systems employed in water resource recovery facilities (WRRF). This review covers available research on the fate of PFAS through incineration systems with a focus on sewage sludge incinerators. This research indicates that at least some PFAS destruction will occur with incineration approaches used at WRRFs. Furthermore, PFAS in flue gas, ash, or water streams used for incinerator pollution control may be undetectable. Future research involving full-scale fate studies will provide insight on the efficacy of PFAS destruction through incineration and whether other compounds of concern are generated.	https://doi.org/10.1002/wer.1483	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid; thermal treatment technologies
September 4, 2020	Screening for 32 per- and polyfluoroalkyl substances (PFAS) including GenX in sludges from 43 WWTPs located in the Czech Republic - Evaluation of potential accumulation in vegetables after application of biosolids	Jaroslav Semerad, Nicolette Hatasova, Alena Grasserova, Tereza Cerna, Alena Filipova, Ales Hanc, Petra Innemanova, Martin Pivokonský, Tomas Cajthaml	Chemosphere	Highly persistent, toxic and bioaccumulative per - and polyfluoroalkyl substances (PFAS) represents a serious problem for the environment and their concentrations and fate remain largely unknown. The present study consists of a PFAS screening in sludges originating from 43 wastewater treatment plants (WWTPs) in the Czech Republic. To analyze an extended group of PFAS consisting of 32 PFAS, including GenX and other new replacements of older and restricted PFAS in sludge, a new method was optimized and validated using pressurized solvent extraction, followed by the SPE clean-up step to eliminate the observed matrix effects and LC-MS/MS. The results revealed high PFAS contamination of sewage sludge, reaching values from 5.6 to 963.2 ng g1. The results showed that in the majority of the samples (about 60%), PFOS was the most abundant among the targeted PFAS, reaching 932.9 ng g1. Approximately 20% of the analyzed samples contained more short-chain PFAS, suggesting the replacement of long-chain PFAS (especially restricted PFOA and PFOS). GenX was detected in 9 samples, confirming the trend in the use of new PFAS. The results revealed that significantly higher contamination was detected in the samples from large WWTPs (population equivalent > 50,000; p-value <0.05). Concerning the application of sludge in agriculture, our prediction using the respective PFAS bioconcentration factors, the observed concentrations, and the legislatively permitted management of biosolids in Czech Republic agriculture revealed that PFAS can cause serious contamination of cereals and vegetables (oat, celery shoots and lettuce leaves), as well as general secondary contamination of the environment.	https://www.sciencedirect.com/science/article/pii/S004565352032213X?via%3Dihub	Sludge; Biosolids; PFAS Fate and Transport; diPAP precusor; evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation
March 3, 2020	Fate of per- and polyfluoroalkyl substances (PFAS) during hydrothermal liquefaction of municipal wastewater treatment sludge	Jie Yu, Anastasia Nickerson, Yalin Li, Yida Fangb and Timothy J. Strathmann	Environmental Science: Water Research & Technology	Hydrothermal liquefaction (HTL) is a promising technology for recovering energy from wastewater treatment sludge in the form of liquid biofuel, but there are concerns about the fate of persistent organic contaminants sorbed to the sludge. This study monitored the fate and degradation of representative per- and polyfluoroalkyl substances (PFAS) in water and sorbed to a municipal wastewater treatment sludge during HTL reactions. The yield and carbon mass content of the biocrude oil product from HTL of sludge increased with increasing reaction temperature from 260 to 300 °C and stabilized with further temperature elevation to 350 °C. Increasing temperature and reaction time also benefited PFAS transformation during the HTL process. Reaction at 350 °C for 90 min led to >99% transformation of fluorinated carboxylic acid structures (perfluorooctanoic acid, PFOA; 7:3 fluorotelomer carboxylic acid, 7:3 FTCA; and 8:2 fluorotelomer unsaturated carboxylic acid, 8:2 FTUCA), but more limited transformation was observed for sulfonic acid structures (34% degradation of perfluorooctane sulfonate, PFOS; 67% degradation of 8:2 fluorotelomer sulfonate, 8:2 FTS). Defluorination data indicates partial mineralization of PFAS during these reactions. Multiphase quantitative analysis shows that the majority of undegraded PFAS partitioned into the HTL biocrude oil product, demonstrating minimal release to the aqueous and solid products, but also indicating the need for monitoring and further purification when upgrading the biocrude oil.	https://pubs.rsc.org/en/content/articlelanding/2020/EW/C9EW01139K	Sludge; Biosolids; Hydrothermal Liquefaction (HTL); biofuel; biocrude oil; PFAS minerialization;

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March 15, 2013	National inventory of perfluoroalkyl substances in archived U.S. biosolids from the 2001 EPA National Sewage Sludge Survey	Arjun K. Venkatesan and Rolf U. Halden	Journal of Hazardous Materials Letters	Using liquid chromatography tandem mass spectrometry, we determined the first nationwide inventories of 13 perfluoroalkyl substances (PFASs) in U.S. biosolids via analysis of samples collected by the U.S. Environmental Protection Agency in the 2001 National Sewage Sludge Survey. Perfluorooctane sulfonate [PFOS; 403 ± 127 ng/g dry weight (dw)] was the most abundant PFAS detected in biosolids composites representing 32 U.S. states and the District of Columbia, followed by perfluorooctanoate [PFOA; 34 ± 22 ng/g dw] and perfluorodecanoate [PFDA; 26 ± 20 ng/g dw]. Mean concentrations in U.S. biosolids of the remaining ten PFASs ranged between 2 and 21 ng/g dw. Interestingly, concentrations of PFOS determined here in biosolids collected prior to the phase-out period (2002) were similar to levels reported in the literature for recent years. The mean load of ΣPFASs in U.S. biosolids was estimated at 2749– 3450 kg/year, of which about 1375–2070 kg is applied on agricultural land and 467–587 kg goes to landfills as an alternative disposal route. This study informs the risk assessment of PFASs by furnishing national inventories of PFASs occurrence and environmental release via biosolids application on land.	https://pubmed.ncbi.nlm.nih.gov/23562984/	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; National Survey; PFAS partitioning