Municipal Biosolids (Sludge) PFAS Treatment Literature

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
May 31, 2025	Experimental investigation on PFAS degradation through municipal sludge combustion processes	M. Urciuolo, R. Migliaccio, B. Ciccone, G. Ruoppolo, A. de Folly d'Auris, S. Frisario, D. Panepinto, G. Premoli, B. Ruffino, M. Zanetti	Applied Thermal Engineering	The incineration of sludge matrices at high temperature (>800 °C) represents a valid solution for per- and polyfluoroalkyl substances (PFAS) abatement. The present study investigates the thermal degradation of sludge samples coming from a municipal wastewater treatment plant, by employing a laboratory-scale continuous bubbling fluidized-bed combustor operating at 850 °C and atmospheric pressure. By utilizing samples of raw municipal sludge and spiked with a known PFAS mixture (up to 8 mg/kg), the research could achieve a high analytical sensitivity, enabling a comprehensive evaluation of PFAS combustion efficiency. Preliminary results elucidated the distribution of PFAS molecules within the combustion byproducts, namely flue gases, fly and bottom ashes, shedding light on the PFAS degradation pathways during incineration. The incineration process was characterized by high combustion efficiency (>96 %).	https://doi.org/10.1016/j.applthermaleng.2025.127006	PFAS remediation; Municipal sludge; Fluidized bed combustor; Thermal degradation
May 19, 2025	Advancing pyrolysis of sewage sludge: Bibliometrics analysis, life cycle assessment, and circular economy insights	Alia Syafiqah Abdul Hamed, Nur Farizan Munajat, Nazaitulshila Rasit, Ismail W. Almanassra, Muataz Ali Atieh, Khalid Sayed, Haif Aljomard	Thermal Science and Engineering Progress	Pyrolysis technology holds great potential for sustainable sewage sludge treatment due to its ability to recover energy, tackle the environmental challenges, and convert by-products into valuable resources. However, a comprehensive understanding of its research progression, sustainability implications, and policy relevance remains limited. This study offers a comprehensive analysis of sewage sludge (SS) pyrolysis research, integrating sustainability through life cycle assessment (LCA) and circular economy principles. Using Scopus and VOSviewer, it highlights significant growth in research, with publications rising in this decade, reflecting increasing global interest driven by environmental and technological imperatives. China dominates the field with 693 publications and extensive international collaborations, followed by the United States and Australia. Key journals play pivotal roles in disseminating findings, while interdisciplinary contributions span environmental science, energy, and chemical engineering. Keyword analysis reveals emerging trends such as circular economy, LCA, and carbon sequestration highlighting a growing focus on sustainable practices. LCA studies show that advanced pyrolysis technologies reduce greenhouse gas emissions, and align with United Nations Sustainable Development Goals. Circular economy analyses underscore the economic viability of co-pyrolysis, alongside substantial energy recovery and bio-oil market potential. Additionally, this study explores the key technological challenges and mitigation strategies crucial for optimizing SS pyrolysis systems and advancing future research. These findings underscore the adaptability of SS pyrolysis for waste valorization and its role in addressing environmental challenges. This analysis provides valuable insights for advancing research, informing policy, and optimizing industrial practices, highlighting SS pyrolysis as a critical technology for sustainable waste management and resource recovery.	https://doi.org/10.1016/j.tsep.2025.103693	Pyrolysis; Sewage Sludge; Biosolids; Renewable Energy; Thermochemical
April 11, 2025	Catalytic and co-hydrothermal treatment of sewage sludge: Hydrochar properties and fate of heavy metals and per and polyfluoroalkyl substances (PFAS)	Kamrun Nahar, Ibrahim Gbolahan Hakeem, Ken Chiang, Andrew S. Ball, Kalpit Shah	Journal of Water Process Engineering	Understanding the fate of heavy metals (HMs) and per and polyfluoroalkyl substances (PFAS) during hydrothermal treatment (HT) of sewage sludge (SS) is crucial for the development and adoption of the HT process for sludge valorisation. However, there are limited understanding on the conversion efficiency of SS, fate of contaminants, product distribution, and hydrochar properties during HT processes, including non-catalytic, catalytic, and co-hydrothermal treatments. Therefore, this study investigates the behaviour and fate of HMs and PFAS in hydrothermal products (hydrochar, bio-oil, and aqueous phase) under sole HT, catalytic HT with $Ca(OH)_2$, and co-HT with alum sludge at 270 °C for 30 min. Catalytic HT and co-HT enhanced bio-oil yields by 10 % and 15 %, respectively, while exhibiting contrasting effects on hydrochar yield. Co-HT increased hydrochar production to 51.3 %, while catalytic HT reduced hydrochar yield to 21 % compared to sole HT of PS. Both processes improved hydrochar porosity, enhancing its potential as an adsorbent. Heavy metals followed distinct pathways, including precipitation, adsorption, co-precipitation, and complexation. Catalytic HT concentrated HMs such as Cu (1151.4 mg/kg) and Zn (1569.5 mg/kg) in hydrochar under alkaline conditions, while co-HT increased mass percentages but diluted their concentrations with Cu and Zn reducing to 660.4 and 467.8 mg/kg. PFAS degradation varies by chemical structure. Approximately >99 % PFOA was degraded during HT, while PFOS degradation was limited, with a maximum of 41 % degradation observed. These findings highlight the need for further process optimisation to improve PFOS breakdown during catalytic HT and co-HT. Overall, this study provides valuable insights into the fate of HMs and PFAS during HT, offering strategies to optimise HT for sustainable sludge management.	https://doi.org/10.1016/j.jwpe.2025.107605	Primary sludge; Alum sludge; Lime catalyst; PFAS degradation; Bio-oil; Heavy metals
March 22, 2025	Understanding dynamics of PFAS in biosolids processed through composting, thermal drying and high temperature pyrolysis	Arifur Rahman, Scott Grieco, Bani Bahman, Andrew Friedenthal, Andrew White, Todd Williams	Journal of Water Process Engineering	Conventional treatment methods are generally ineffective in removing PFAS (per- and polyfluoroalkyl substances) from liquid or solid streams in Water Resource Recovery Facilities (WRRFs). This poses a challenge for utilities, as the future regulation of PFAS is evolving, creating uncertainty in planning process upgrades. To support utilities and biosolids producers, this study evaluated several biosolids products (from 15 plants) through treatment process of composting (aerobic), thermal drying, and high temperature pyrolysis, all derived from non-industrially impacted sources. This study conducted an analysis of these products, focusing on the concentration of PFAS in the final products and the effectiveness of these treatment processes in reducing or eliminating PFAS from the initial feed solids. The composting results indicated that when sludge (waste activated sludge (WAS) or mixture of primary sludge and WAS) processed through liquid aerobic activated sludge treatment, the total concentration of the quantified PFAS in composting material was reduced by 9–20 % compared to raw sludge. In addition, when sludge processed through both liquid aerobic treatment and anaerobic digestion process, precursor transformation in composts is comparatively less compared to primary sludge. Samples (dewatered cake from primary sludge + WAS) collected from biological nutrient removal plant showed that reduction of PFAS compounds through the thermal drying system can be obtained with an average overall reduction of 15–31 %. In addition, a positive linear relationship was observed between thermal dryer inlet temperature and quantified PFAS reduction (high temperature indicates higher removal). A bench-scale pyrolysis setup was conducted on anaerobically digested dried solids which was pyrolyzed at 700 °C and achieved over 99 % PFAS mass reduction of measurable PFAS.	https://doi.org/10.1016/j.jwpe.2025.107508	Biochar; Biosolids; Dewatered cake; PFAS; PFOS; Pyrogas

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March 22, 2025	Rethink biosolids: Risks and opportunities in the circular economy	Jinkai Xue, Willy Verstraete, Bing-Jie Ni, John P. Giesy, Guneet Kaur, Daqian Jiang, Edward McBean, Zhenyu Li, Hyeong-Moo Shin, Feng Xiao, Yang Liu, Jinyong Liu, Leah Chibwe, Kelvin Tsun Wai Ng, Yoshitaka Uchida	Chemical Engineering Journal	Biosolids are a byproduct of wastewater treatment with potential value because of their rich nutrient, organic matter, and mineral content. However, due to the environmental and public health risks posed by contaminants, such as per- and polyfluoroalkyl substances (PFAS), micro-/nano-plastics (MNPs), and antibiotic resistance genes (ARGs), the conventional practice of applying biosolids to land, especially on agricultural lands, can be unsustainable. These contaminants can accumulate in soil, disrupt ecosystems, and pose long-term risks to food safety and human health. Through the lens of a circular economy, biosolids should be valorized through holistic and sustainable approaches that prioritize both environmental protection and resource recovery. Advanced technologies, such as anaerobic membrane bioreactors, pyrolysis, and hydrothermal liquefaction, can extract valuable resources, such as energy and bioplastics, while also destroying harmful contaminants. In addition, biosolids and biosolids-derived biochar hold untapped potential for carbon capture and storage (CCS), offering a sustainable alternative to land applications while also helping mitigate climate change. Hence, a circular economy approach not only minimizes waste and reduces environmental impacts but also unlocks an important potential of biosolids as a renewable resource moving forward.	https://doi.org/10.1016/j.cej.2025.161749	Sewage sludge; Sanitation residuals; CEC; PFAS; Microplastics; Nanoplastics; ARG; AMR; Emerging pollutants; Carbon capture and storage; Resource recovery
January 30, 2025	The fate of per- and polyfluoroalkyl substances (PFAS) during pyrolysis and co-pyrolysis of biosolids with alum sludge and wheat straw	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	Journal of Analytical and Applied Pyrolysis	The literature suggests that the pyrolysis of biosolids merely volatilizes per- and polyfluoroalkyl substances (PFAS) into gas or liquid phase, requiring a thermal oxidizer operating at 900–1200 ºC with more than 2 second residence time, to destroy the volatilized PFAS. This study investigates the potential and extent of destruction of PFAS under pyrolysis environment. Pyrolysis and co-pyrolysis experiments were conducted in a bench-scale horizontal fixed-bed reactor. Co-pyrolysis experiments was carried out by blending biosolids with alum sludge or wheat straw at a 1:1 (w/w) mixing ratio at 600 ◦C. Gas and solids residence times in the reactor were approximately 10 seconds and 1 hour, respectively. The study also explored the effects of lime and biochar as catalysts on PFAS destruction. Results showed near complete removal of PFAS from biochar with the total PFAS concentration reducing from 409.9 ng/g in biosolids to 0.31 ng/g in biochar, suggesting significant volatilization or decomposition at 600 ◦C. However, PFAS concentrations in volatile products were also significantly low (5.5 ng/g in bio-oil and 0.15 ng/g in scrubber water), indicating 99.4 % PFAS destruction efficiency. The co-pyrolysis of biosolids further improved PFAS removal, likely due to dilutive and synergistic effects. However, catalysis with lime and biochar did not have a significant effect on the PFAS destruction efficiency. This research highlights the potential for near complete PFAS destruction in pyrolysis and co-pyrolysis under the current experimental conditions but emphasizes the need for further investigations under the operational parameters of large-scale pyrolysis plants.	https://doi.org/10.1016/j.jaap.2025.106970	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
December 29, 2024	Evaluation of PFAS extraction and analysis methods for biosolids	Caroline Rose Alukkal, Mahsa Modiri, Rodrigo Alvarez Ruiz, Youn Jeong Choi, Linda S. Lee	Talanta	Per- and polyfluoroalkyl substances (PFAS) in the environment is a growing concern leading to a focus on PFAS occurrence in biosolids, a byproduct of wastewater treatment processes, often applied to improve soil health. This led to the need for analytical method development for assessing PFAS in biosolids. This study compares three methods for PFAS quantitation, evaluating solvent extraction, clean-up techniques, and final injection solvents. Three biosolids examined included not stabilized, anaerobically digested, and activated sludge with long-term lagoon-stabilized solids, resulting in differing properties. One method is a methanolic extraction with ENVI-Carb clean-up (ME), modified by adding isopropanol (ME-P) to the injection vial to prevent emulsification that can occur with more complex biosolids matrices. The second method was the U.S. EPA 1633 method involving additional solid-phase extraction (SPE) and filtration while the third method was Quick Easy Cheap Effective Rugged and Safe (QuEChERS), yet to be tested on biosolids. Method performance was evaluated based on instrument precision, limit of quantitation (LOQ), and extraction recoveries. PFAS concentrations and recoveries were similar for Me-P and 1633 methods while QuEChERS performed poorly. Method 1633 exhibited better reproducibility with lower relative standard deviations but had higher LOQ values due to sample dilution. Most LOQs ranged between 0.06 and 0.3 mug/kg across methods, while recovery of spiked native PFAS ranged between 70 and 130 % in most cases. Methanol-based mobile phases resulted in better peak shape. ME-P excelled in overall cost-effectiveness showing superior extraction efficiency with fewer operational steps compared to other methods for PFAS quantitation in biosolids.	https://doi.org/10.1016/j.talanta.2024.127485	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment

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December 18, 2024	Perfluoroalkyl and polyfluoroalkyl substances in sewage sludge: challenges of biological and thermal treatment processes and potential threats to the environment from land disposal	Olga S. Arvaniti, Michail S. Fountoulakis, Georgia Gatidou, Olga-Ioanna Kalantzi, Stergios Vakalis, Athanasios S. Stasinakis	Environmental Sciences Europe	Sewage treatment plants are considered as important pathways for the transfer of perfluoroalkyl and polyfluoroalkyl sub- stances (PFAS) to the environment. In conventional wastewater treatment, some of these compounds accumulate in sew- age sludge via sorption onto suspended solids posing a potential environmental threat during sludge disposal and reuse. This review paper summarizes data for the occurrence of 182 PFAS from different classes in sludge matrices. Most of these monitoring data originate from Europe, Asia and North America, while limited data are available from Africa and South America. The most commonly studied classes of PFAS are perfluoroalkyl carboxylic acids, perfluoroalkyl sulfonic acids, and perfluoroalkyl sulfonamides, while few results are available for the occurrence of new generation PFAS such as GenX. The range of the observed concentrations varies between 0.01 ng/g d.w. for perfluorobutane sulfonic acid to some μg/g, depending on the compound, with the highest concentrations found for perfluorooctane sulfonic acid (8.2 μg/g d.w.). Limited information exists for the fate and removal of these substances in full-scale anaerobic digesters while recent articles indicate that some PFAS can be biotransformed under strictly anaerobic conditions. The exact mechanism remains unclear; additional data are needed to identify transformation products, apply mass balances, and understand the role of specific microorganisms. As regards novel thermal processes, encouraging results were recently published for the destruction of specific PFAS in hydrothermal liquefaction and carbonization, ranging between 55 and 100%, depending on the com- pound and the experimental conditions applied. Future studies should expand the list of studied compounds and focus on the mechanisms of their removal. PFAS are transferred to agricultural lands during sewage sludge reuse and their concentrations in soil are related to the applied biosolids' loading rates. The parameters that affect leaching and desorption of PFAS from sludge, their plant uptake and possible threats for the environment and human health from the use of sew- age sludge as soil amendment should be examined in long-term studies. ZeroPM project aims to address some of the lit- erature gaps regarding the behavior of PFAS during sludge treatment focusing to the modification of anaerobic digestion and to the use of hydrothermal carbonization.	https://doi.org/10.1186/s12302-024-01031-3	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
December 2, 2024	Leaching profile of per- and polyfluoroalkyl substances (PFAS) from biosolids after thickening, anaerobic digestion, and dewatering processes, and significance of protein, phosphorus, and selected ions	Yelena Katsenovich, Berrin Tansel, Natalia Soares Quinete, Zariah Nasir, Joshua Omaojo Ocheje, Maria Mendoza Manzano	Science of the Total Environment	Batch leaching experiments were conducted to evaluate the release of forty per- and polyfluoroalkyl substances (PFAS) from sludge samples collected after thickening, anaerobic digestion, and dewatering processes at two wastewater treatment plants. The South District wastewater treatment plant (SDWWTP), which receives domestic wastewater and landfill leachate from a nearby landfill, and the Central District wastewater treatment plant (CDWWTP), which receives only domestic wastewater, were selected for this study. PFAS released into the aqueous phase were analyzed by sacrificial sampling after 1, 3, 7, 14, and 30 days. Results demonstrated rapid PFAS leaching, with the highest levels detected in biosolid leachates after just one day. Distinct differences were observed in PFAS composition and concentrations between the two treatment plants. Of the forty PFAS measured, nineteen were detected, with higher concentrations identified at SDWWTP. The input of landfill leachate to SDWWTP appears to have significantly contributed to the elevated levels of specific PFAS, particularly long-chain compounds, compared to the emerging short-chain PFAS found in biosolids. In addition to PFAS analysis, the compositions of the sludge samples, including total and volatile solids, protein, phosphorus (P), iron, aluminum, calcium, and magnesium, were also assessed. Spearman correlation analyses revealed moderate to strong relationships between PFAS levels in leachate and certain sludge components. For instance, correlations between P content and PFCAs and FTCAs were moderate (R(2) = 0.45-0.76). In thickener sludge leachate, strong correlations were observed for FPrPA (3:3 FTCA), PFDA, and PFTrDA with P, with R(2) values of 0.60, 0.53, and 0.54, respectively. In the digested sludge, correlations were found for PFHpA, PFDA, and PFNA (R(2) = 0.45-0.76). Also, for digested sludge leachate, strong correlations were found between the individual compounds PFHpA, PFHxA, PFNA, PFOA, and PFPeA (R(2) = 0.60-0.88). Predominant PFAS in leachate from biosolids were identified, including PFOS, FPePA (5:3 FTCA), PFPeA, PFBA, PFHxA, N-EtFOSAA, and 6-2 FTS.	https://doi.org/10.1016/j.scitotenv.2024.177777	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
November 26, 2024	State of the science and regulatory acceptability for PFAS residual management options: PFAS disposal or destruction options	Mahsa Modiri, Pavankumar Challa Sasi, Kyle A. Thompson, Linda S Lee, Katie Marjanovic, Graeme Hystad, Kamruzzaman Khan, John Norton	Chemosphere	This systematic review covers the urgent challenges posed by per- and polyfluoroalkyl substances (PFAS) in managing residuals from municipal, industrial, and waste treatment sources. It covers regulatory considerations, treatment technologies, residual management strategies, and critical conclusions and recommendations. A rigorous methodology was employed, utilizing scientific search engines and a wide array of peer-reviewed journal articles, technical reports, and regulatory guidance, to ensure the inclusion of the most relevant and up-to-date information on PFAS management of impacted residuals. The increasing public and regulatory focus underscores the persistence and environmental impact of PFAS. Emerging technologies for removing and sequestrating PFAS from environmental media are evaluated, and innovative destruction methods for addressing the residual media and the concentrated waste streams generated from such treatment processes are reviewed. Additionally, the evolving regulatory landscape in the United States is summarized and insights into the complexities of PFAS in residual management are discussed. Overall, this systematic review serves as a vital resource to inform stakeholders, guide research, and facilitate responsible PFAS management, emphasizing the pressing need for effective residual management solutions amidst evolving regulations and persistent environmental threats.	https://doi.org/10.1016/j.chemosphere.2024.143726	PFAS; Residuals; Wastewater treatment plants; Separation; Destruction

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November 16, 2024	Analytical protocol for detection and prioritization of per- and polyfluoroalkyl substances (PFAS) in biosolid leachates	Joshua Omaojo Ocheje, Maria Mendoza Manzano, Zariah Nasir, Yelena Katsenovich, Berrin Tansel, Shyam Sivaprasad, Natalia Quinete	Journal of Water Process Engineering	Land application of biosolids from wastewater treatment plants (WWTPs) can potentially release per- and polyfluoroalkyl substances (PFAS) into the environment. Limited data is available on PFAS types and levels in biosolids from South Florida. This study outlines analytical protocols for detecting and quantifying PFAS in biosolid leachate and solid residue, by modifying and validating a method based on the U.S. EPA Method 1633. The method achieved detection limits as low as 0.02 ng/L in leachate and 0.01 ng/g in the biosolid residues and was applied to samples from two Miami-Dade WWTPs, in which 22 of 40 targeted PFAS were detected in leachates and 19 in solid residues after leaching. Distinct PFAS composition and levels were observed among the WWTPs, whereas the sum of PFAS (∑22PFAS) in leachates ranged from 57 to 463 ng/L, and in the solid residue ∑19PFAS ranged from 187 to 571 ng/g. The 5:3 Fluorotelomer carboxylic acid (5:3 FTCA) was the most prevalent and abundant PFAS found, with a detection frequency between 83 % and 100 %. Key PFAS were prioritized based on their concentration and detection frequency. These findings highlight PFAS occurrence and distribution in biosolids at different treatment stages, underscoring the need for further monitoring and regulation.	https://doi.org/10.1016/j.jwpe.2024.106546	PFAS; Sludge; Wastewater treatment plants; South Florida; Liquid-chromatography mass spectrometry
November 12, 2024	Fate of biosolids-bound PFAS through pyrolysis coupled with thermal oxidation for air emissions control	Lloyd J. Winchell, Joshua Cullen, John J. Ross, Alex Seidel, Mary Lou Romero, Farokh Kakar, Embrey Bronstad, Martha J. M. Wells, Naomi B. Klinghoffer, Franco Berruti, Alexandre Miot, Katherine Y. Bell	Water Environmental Research	Pyrolysis has been identified as a possible thermal treatment process for reducing perfluoroalkyl and polyfluoroalkyl substances (PFAS) from wastewater solids, though off-gas from the pyrolysis unit can still be a source of PFAS emissions. In this work, the fate of PFAS through a laboratory-scale pyrolysis unit coupled with a thermal oxidizer for treatment of off-gasses is documented. Between 91.5% and >99.9% reduction was observed through the entire system for specific compounds based on targeted analyses. Overall, the pyrolysis and thermal oxidizer system removed 99.4% of the PFAS moles introduced. Furthermore, shorter chain variants comprised the majority of reportable PFAS in the thermal oxidizer flue gas, indicating the longer chain compounds present in the dried biosolids fed to pyrolyzer decompose through the system.	https://doi.org/10.1002/wer.11149	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
September 19, 2024	Comparing occurrence of per- and polyfluoroalkyl substances (PFAS) in municipal biosolids and industrial wastewater sludge: A City of Los Angeles study	Ochan Otim	Science of The Total Environment	Biosolids and sludge are what remain after the liquid fraction of wastewater is separated during wastewater treatment. These high organic content matrices are known to contain organic contaminants, a few of which are the hazardous and environmentally persistent per- and polyfluoroalkyl substances (PFAS). The current study investigates whether sludge from a treatment facility serving mostly industrial establishments and biosolids from a facility serving mostly domestic dwellings retain these 'forever chemicals' similarly. Using 31 markers covering different classes of PFAS, the sludge was found to contain higher levels of PFAS (869 ± 791 ng/g; 21 of 31) than biosolids (31 ± 7 ng/g, 11 of 31). The most abundant overall was perfluorooctane sulfonic acid (PFOS), mostly in sludge (range: 71–1300 ng/g versus 0–18 ng/g in biosolids). The large PFAS concentration variability in sludge was seasonal and sinusoidal. Sludge, additionally, contained all long chain PFAS, precursors (mostly surfactant ingredients and their transformation byproducts) and short chain PFAS (perhaps because of higher moisture content). By regression, the sludge is shown to consistently contain twice as much PFAS as biosolids when the same amounts are exposed to increasing levels of PFAS. Factors observed to cause differential PFAS retention between sludge and biosolids were moisture (98.6 % and 72.1 %, respectively), chain length, input quality (industrial versus residential) and functional group. Sulfonic acids for instance are one C atom shorter than carboxylates with similar occurrence in sludge and biosolids. More studies are needed to define the roles that organic carbon of sludge/biosolids, water chemistry, temperature and factors not considered here play in partitioning PFAS between the two matrices with respect to inputs. Existing Koc values could not help in explaining observed trends, but the ratio of biosolids-to-influent concentrations was found to correlate positively with PFAS size. Using influent in the ratio, and not effluent, is novel.	https://doi.org/10.1016/j.scitotenv.2024.176268	PFAS; Municipal biosolids; Industrial sludge; Solid-liquid partition ratio
September 11, 2024	Can pyrolysis and composting of sewage sludge reduce the release of traditional and emerging pollutants in agricultural soils? Insights from field and laboratory investigations	Niluka Wickramasinghe, Martina Vítková, Szimona Zarzsevszkij, Petr Ouředníček, Hana Šillerová, Omolola Elizabeth Ojo, Luke Beesley, Alena Grasserová, Tomáš Cajthaml, Jaroslav Moško, Matěj Hušek, Michael Pohořelý, Jarmila Čechmánková, Radim Vácha, Martin Kulhánek, Alena Máslová, Michael Komárek	Chemosphere	The potential extractability, crop uptake, and ecotoxicity of conventional and emerging organic and metal(loid) contaminants after the application of pre-treated (composted and pyrolysed) sewage sludges to two agricultural soils were evaluated at field and laboratory scale. Metal(loid) extractability varied with sludge types and pre-treatments, though As, Cu, and Ni decreased universally. In the field, the equivalent of 5 tons per hectare of both composted and pyrolysed sludges brought winter wheat grain metal(loid) concentrations below statutory limits. Carbamazepine, diclofenac, and telmisartan were the only detected organic pollutants in crops decreasing in order of root > shoot > grains, whilst endocrine-disrupting chemicals, such as bisphenol A and perfluorochemicals were heavily reduced by composting (up to 71%) or pyrolysis (up to below detection limit) compared to raw sludges. As a consequence, no detectable concentrations were measured in soils 12 months after field application. This study highlights the potential advantages of processing sewage sludge before soil applications, especially in the context of reducing the mobility of emerging contaminants, though further studies are required on a broad range of soils and crops before land application can be considered.	https://doi.org/10.1016/j.chemosphere.2024.143289	Composted sludge; Endocrine disrupting compounds; PFAS; Pyrolysed sludge; Metal(loid)s

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September 9, 2024	On safety of sewage biosolids valorisation: Distribution of PFAS, PAHs, PCDD/Fs, and heavy metals in low-temperature pyrolysis end-products for agricultural and energetic applications	Felizitas Schlederer, Edgar Martín-Hernández, Céline Vaneeckhaute	Chemical Engineering Journal	Pyrolysis is a suitable process for sewage sludge valorisation while potentially reducing micropollutants. However, previous studies mainly focused on micropollutants in biochar, neglecting their presence of aqueous pyrolysis liquid (APL), pyrolysis oil, and gas. This study analyses the distribution of 66 micropollutants, including PFAS, dioxins and furans (PCDD/Fs), heavy metals (HMs), and polycyclic aromatic hydrocarbons (PAHs) across biochar, APL and pyrolysis oil. Additionally, the impact of a carrier gas supply (N2 and CO2) on micropollutants distribution was evaluated. In a second stage, the safe use of the pyrolysis end-products for agricultural and energetic purposes was explored. PFAS from biosolids were distributed in biochar (12–13 %), APL (6–7 %), and the oil phase (2–5 %). 63–74 % remained unaccounted for, possibly transferred to the gas phase, or decomposed during pyrolysis. PAHs were predominantly found in the pyrolysis oil, while PCDD/Fs were found in the biochar and pyrolysis oil. HMs were primarily found in biochar. PAH and PCDD/F values in the biochar met the European Biochar Certificate (EBC) guidelines. However, HMs surpassed the thresholds, suggesting either post-treatment or using biochar as a building material instead. Given that pyrolysis oil contains significant quantities of micropollutants, high-temperature combustion could serve for both micropollutant decomposition and energy reclamation. Energetic valorisation of APL assessed by biomethane potential tests, achieved a methane production yield of 432–450 NmLCH4/gVS. Overall, a combined anaerobic digester and pyrolysis process, including a recirculation of the APL, the valorisation of pyrolysis oil for process heating, and the use of CO2 from biogas as pyrolysis carrier gas, is suggested for further study.	https://doi.org/10.1016/j.cej.2024.155534	Biosolids pyrolysis; Micropollutant distribution; Biochar; Aqueous pyrolysis liquid; Pyrolysis oil
August 9, 2024	Current understanding on the fate of contaminants during hydrothermal treatment of sewage sludge	Kamrun Nahar, Adhithiya Venkatachalapati Thulasiraman, Arun Krishna Vuppaladadiyam, Ibrahim Gbolahan Hakeem, Kalpit Shah	Current Opinion in Green and Sustainable Chemistry	Sewage sludges (SS) are by-products of the wastewater treatment process and are considered critical source of contaminants as they contain a diverse range of microbial, organic, and inorganic pollutants that are concerning to public health and the environment. Hydrothermal processes are particularly suitable for treating SS; however, their viability for the effective degradation and potential destruction of persistent contaminants, such as heavy metals, microbial pathogens, microplastics, per- and polyfluoroalkyl substances, pharmaceuticals, and personal care products, among others in SS is still under rapid investigations. This article reviews the source, transformation, and fate of prominent contaminants in SS during hydrothermal treatment (HT). Most contaminants in SS are to a certain extent degraded or transformed into other products under typical HT at subcritical conditions. Transformation pathways can be complex due to the diverse physicochemical and biochemical properties, including thermal stability and hydrophobicity. Critical findings were summarised with conclusions and perspectives for future works provided.	https://doi.org/10.1016/j.cogsc.2024.100960	Contaminants destruction; Heavy metals; Microplastics; Per- and polyfluoroalkyl substances; Hydrochar; Thermal processing
July 15, 2024	The Fate of Fluorine Post Per- and Polyfluoroalkyl Substances Destruction during the Thermal Treatment of Biosolids: A Thermodynamic Study	S. Patel, P. Halder, I. G. Hakeem, E. Selezneva, M. K. Jena, G. Veluswamy, et al.Savankumar Patel, Pobitra Halder, Ibrahim Gbolahan Hakeem, Ekaterina Selezneva, Manoj Kumar Jena, Ganesh Veluswamy, Nimesha Rathnayake, Abhishek Sharma, Anithadevi Kenday Sivaram, Aravind Surapaneni, Ravi Naidu, Mallavarapu Megharaj, Arun K. Vuppaladadiyam, Kalpit Shah	Energies	Per- and polyfluoroalkyl substances (PFAS) are a group of fluorinated synthetic chemicals that are highly recalcitrant, toxic, and bio-accumulative and have been detected in biosolids worldwide, posing potential risks to humans and the environment. Recent studies suggest that the organic C-F bond in PFAS can be destructed and potentially mineralised into inorganic fluorides during thermal treatment. This study focuses on thermodynamic equilibrium investigations and the fate of fluorine compounds post-PFAS destruction during biosolid thermal treatment. The results indicate that gas-phase fluorine compounds are mainly hydrogen fluoride (HF) and alkali fluorides, whereas solid-phase fluorine compounds include alkaline earth fluorides and their spinels. High moisture and oxygen content in the volatiles increased the concentration of HF in the gas phase. However, adding minerals reduced the emission of HF in the gas phase significantly and enhanced the capture of fluorine as CaF2 spinel in the solid phase. This study also investigates the effect of feedstock composition on the fate of fluorine. High ash content and low volatile matter in the feedstock reduced HF gas emissions and increased fluorine capture in the solid product. The findings of this work are useful in designing thermal systems with optimised operating conditions for minimising the release of fluorinated species during the thermal treatment of PFAS-containing biosolids.	https://doi.org/10.3390/en17143476	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
July 14, 2024	Elimination of microplastics, PFAS, and PPCPs from biosolids via pyrolysis to produce biochar: Feasibility and techno-economic analysis	Arturo A. Keller, Weiwei Li, Yuki Floyd, James Bae, Kayla Marie Clemens, Eleanor Thomas, Ziwei Han, Adeyemi S. Adeleye	Science of the Total Environment	Biosolids from municipal wastewater treatment contain many contaminants of emerging concern, including microplastics (MPs), per- and polyfluoroalkyl substances (PFAS), pharmaceuticals and chemicals from personal care products (PPCPs). Many of these contaminants have very slow biotic or abiotic degradation rates and have been shown to have human and ecological health impacts. Application of biosolids to agriculture, a common disposal method, can result in extended environmental contamination. An approach for eliminating the contaminants is pyrolysis, which can also generate biochar, enhancing carbon sequestration as a side-benefit. We pyrolyzed biosolid samples from an operating facility at various temperatures from 400 to 700 degrees C with a 2-hour residence time. We then evaluated contaminant removal, which in many cases was 100 %, with only a few residuals. No trace of PFAS was detectable even at 400 degrees C. Overall mass removal of PPCPs, including PFAS, was over 99.9 %. MP removal via pyrolysis ranged from 91 to 97 %. The biochar contains significant amounts of Fe and P, which make it a useful fertilizer amendment. The techno-economic analysis indicates that pyrolysis may generate significant cost savings, and revenue from the sale of biochar, sufficient to more than cover the investment and operating costs of the dryer and pyrolysis unit.	https://doi.org/10.1016/j.scitotenv.2024.174773	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment

Municipal Biosolids (Sludge) PFAS Treatment Literature

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
July 14, 2024	Surveillance of PFAS in sludge and biosolids at 12 water resource recovery facilities	Shubhashini Oza, Katherine Y. Bell, Zhiliang Xu, Yifei Wang, Martha J. M. Wells, John W. Norton Jr., Lloyd J. Winchell, Qingguo Huang, Hui Li	Journal of Environmental Quality	Per- and polyfluoroalkyl substances (PFAS) are refractory anthropogenic chemicals and current treatment processes at municipal water resource recovery facilities (WRRFs) cannot efficiently degrade them, hence, these chemicals cycle through the environment. Certain PFAS can be concentrated in biosolids from WRRFs and are commonly land applied for beneficial reuse. Given recent advances in measurement of PFAS, documentation of the range of concentrations in pre-stabilized sludge and stabilized biosolids is critical to evaluating treatment best practices and assessing potential human health and ecological risks. In this study, pre-stabilized sludge and post-stabilized biosolids samples were collected from 12 major WRRFs across the United States. PFAS were analyzed using Environmental Protection Agency (EPA) Method SW846-3500C/537.1, and Draft EPA Method 1633, by one commercial laboratory and two university research laboratories, respectively. Results comparison among laboratories demonstrated statistical differences in PFAS concentrations among split samples. For example, 5:3 FTCA (fluorotelomer carboxylic acid) concentrations in post-stabilized sludge at Lab 1 were measured at 21 ng/g (dry), while they were detected at 151 ng/g (dry) in Lab 3. Further, higher PFAS concentrations were observed in post-stabilized biosolids compared to pre-stabilized sludges, regardless of the laboratory or analysis method, even when solids destruction through solids stabilization was considered. Further research is required to refine methods for analyses of PFAS in sludge and biosolids samples from WRRFs prior to being used for development of regulatory actions as well as understanding how various treatment protocols could impact concentrations of PFAS in land-applied biosolids.	https://doi.org/10.1002/jeq2.20595	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
June 5, 2024	Current understanding on the transformation and fate of per- and polyfluoroalkyl substances before, during, and after thermal treatment of biosolids	Ibrahim Gbolahan Hakeem, Pobitra Halder, Savankumar Patel, Ekaterina Selezneva, Nimesha Rathnayake, Mojtaba Hedayati Marzbali, Ganesh Veluswamy, Abhishek Sharma, Sazal Kundu, Aravind Surapaneni, Mallavarapu Meghara, Damien J. Batstone, Kalpit Shah	Chemical Engineering Journal	Biosolids (stabilised sewage sludge) are the final solid residues of the wastewater treatment process and are generally applied on agricultural land in many countries, including Australia. Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic fluorinated chemicals with ubiquitous applications in consumer products and persist in the environment. Globally, PFAS have been detected in biosolids and are considered a source of PFAS discharge to the environment. The thermal treatment of biosolids is gaining increasing interest in the water sector. Therefore, the viability of thermal techniques for the safe destruction of PFAS has received substantial research attention in the last few years. Recent studies suggest that PFAS in biosolids can be removed and potentially destroyed during combustive (such as incineration) and non-combustive thermal treatment, such as pyrolysis, gasification, and hydrothermal carbonisation/liquefaction. However, there is limited understanding on the fate and transformation of PFAS degradation products across the overall thermal treatment process from biosolids feed pre-treatment to the gas cleaning (post-thermal treatment) stage. This review consolidates the current knowledge on PFAS transformation, destruction, and final fate before, during, and after thermal treatment of biosolids, covering lab, pilot scale, and industrial studies. It is suggested that PFAS degradation mechanisms during thermal treatment of biosolids may differ from the established pathways for pure PFAS salts, given that biosolids have a complex organic and inorganic matrix and typically have low PFAS concentrations. Among all thermal treatment techniques, pyrolysis has received extensive investigations at different scales of operation. However, for all techniques, treatment temperatures and residence time need to be sufficiently optimised for designing realistic large-scale thermal systems relevant to biosolids' compositional peculiarities for PFAS destruction.	https://doi.org/10.1016/j.cej.2024.152537	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
March 19, 2024	Biosolids, an important route for transporting poly- and perfluoroalkyl substances from wastewater treatment plants into the environment: A systematic review	Ali Behnami, Khaled Zoroufchi Benis, Mojtaba Pourakbar, Mojtaba Yeganeh, Ali Esrafili, Mitra Gholami	Science of the Total Environment	The pervasive presence of poly- and perfluoroalkyl substances (PFAS) in diverse products has led to their introduction into wastewater systems, making wastewater treatment plants (WWTPs) significant PFAS contributors to the environment. Despite WWTPs' efforts to mitigate PFAS impact through physicochemical and biological means, concerns persist regarding PFAS retention in generated biosolids. While numerous review studies have explored the fate of these compounds within WWTPs, no study has critically reviewed their presence, transformation mechanisms, and partitioning within the sludge. Therefore, the current study has been specifically designed to investigate these aspects. Studies show variations in PFAS concentrations across WWTPs, highlighting the importance of aqueous-to-solid partitioning, with sludge from PFOS and PFOA-rich wastewater showing higher concentrations. Research suggests biological mechanisms such as cytochrome P450 monooxygenase, transamine metabolism, and beta-oxidation are involved in PFAS biotransformation, though the effects of precursor changes require further study. Carbon chain length significantly affects PFAS partitioning, with longer chains leading to greater adsorption in sludge. The wastewater's organic and inorganic content is crucial for PFAS adsorption; for instance, higher sludge protein content and divalent cations like calcium and magnesium promote adsorption, while monovalent cations like sodium impede it. In conclusion, these discoveries shed light on the complex interactions among factors affecting PFAS behavior in biosolids. They underscore the necessity for thorough considerations in managing PFAS presence and its impact on environmental systems.	https://doi.org/10.1016/j.scitotenv.2024.171559	Per- and polyfluoroalkyl substance; PFAS; Wastewater treatment plant; Biosolids

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. Practitioner Points: ▪The MHF emitted six short chain PFAS from the stack, which were shorter alkyl chain compounds compared with sludge PFAS. ▪The FBF did not consistently emit reportable PFAS from the stack, but contamination complicated the assessment. ▪Five percent of the MHF sludge molar PFAS load was reported in the stack. ▪MHF and FBF wet scrubber water streams accumulated nonpolar fluorinated organics from the furnace exhaust. ▪Ultra-short volatile alkane PFAS measured at the stack represented 0.5%–4.5% of the 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
February 1, 2024	Occurrence, fate, and remediation for per- and polyfluoroalkyl substances (PFAS) in sewage sludge: A comprehensive review	Ting Zhou, Xuan Li, Huan Liu, Shiman Dong, Zehao Zhang, Zhenyao Wang, Jibin Li, Long D. Nghiem, Stuart J. Khan, Qilin Wang	Journal of Hazardous Materials	Addressing per-and polyfluoroalkyl substances (PFAS) contamination is an urgent environmental concern. While most research has focused on PFAS contamination in water matrices, comparatively little attention has been given to sludge, a significant by-product of wastewater treatment. This critical review presents the latest information on emission sources, global distribution, international regulations, analytical methods, and remediation technologies for PFAS in sludge and biosolids from wastewater treatment plants. PFAS concentrations in sludge matrices are typically in hundreds of ng/g dry weight (dw) in developed countries but are rarely reported in developing and least-developed countries due to the limited analytical capability. In comparison to water samples, efficient extraction and cleaning procedures are crucial for PFAS detection in sludge samples. While regulations on PFAS have mainly focused on soil due to biosolids reuse, only two countries have set limits on PFAS in sludge or biosolids with a maximum of 100 ng/g dw for major PFAS. Biological technologies using microbes and enzymes present in sludge are considered as having high potential for PFAS remediation, as they are eco-friendly, low-cost, and promising. By contrast, physical/chemical methods are either energy-intensive or linked to further challenges with PFAS contamination and disposal. The findings of this review deepen our comprehension of PFAS in sludge and have guided future research recommendations.	https://doi.org/10.1016/j.jhazmat.2024.133637	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
January 22, 2024	Is removal and destruction of perfluoroalkyl and polyfluoroalkyl substances from wastewater effluent affordable?	Alison L. Ling, Rebecca R. Vermace, Andrew J. McCabe, Kathryn M. Wolohan, Scott J. Kyser	Water Environment Research	Several jurisdictions are currently evaluating regulatory standards for perfluoroalkyl and polyfluoroalkyl substances (PFAS) in municipal water resource recovery facility (WRRF) effluent. Effective and responsible implementation of PFAS effluent limits should consider the costs and capabilities of currently available technologies, because the costs of meeting WRRF PFAS limits could disproportionally fall to ratepayers. Cost curves were developed for currently available PFAS separation and destruction options, assuming effluent treatment targets near current analytical detection limits. Removing and destroying PFAS from municipal WRRF effluent is estimated to increase costs per household by a factor of between 2 and 210, using Minnesota-specific data as an example. Estimated costs per household would increase more for residents of smaller communities, averaging 33% of median household income (MHHI) in communities smaller than 1000 people. This exceeds the U.S. Environmental Protection Agency (EPA)-developed affordability index of 2% of MHHI by a factor of 16. Estimated costs per household to remove and destroy PFAS varied among locations, primarily based on WRRF and community size, median income, rural versus urban, and type of wastewater treatment processes currently used.	https://doi.org/10.1002/wer.10975	PFAS, PFAS destruction, PFAS Treatment, Wastewater affordability, Cost burden, Water resource recovery facility (WRRF)
January 15, 2024	Ensuring safety standards in sewage sludge-derived biochar: Impact of pyrolysis process temperature and carrier gas on micropollutant removal	Felizitas Schlederer, Edgar Martín-Hernández, Céline Vaneeckhaute	Journal of Environmental Management	The application of sewage sludge to agricultural land is facing increasing restrictions due to concerns about various micropollutants, including polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDD/Fs), polychlorinated biphenyls (PCBs), per- and poly-fluoroalkyl substances (PFAS), and heavy metals (HMs). As an alternative approach to manage this residue, the use of pyrolysis, a process that transforms sludge into biochar, a carbon-rich solid material, is being explored. Despite the potential benefits of pyrolysis, there is limited data on its effectiveness in removing micropollutants and the potential presence of harmful elements in the resulting biochar. This study aims to evaluate the impact of the temperature and the use of a carrier gas (N2) during a two-stage pyrolysis and cooling on micropollutant removal. Pilot-scale tests showed that a higher temperature (650 °C) and the use of a carrier gas (0.4 L/min N2) during the pyrolysis and the cooling process led to a reduction of PAHs, PCDD/Fs, PCBs and PFAS below their detection limits. As such, the generated biochar aligns with the guidelines set by the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC) for all micropollutants, except for zinc and copper. Additional investigation is required to determine whether the micropollutants undergo destruction or transition into other pyrolysis end-products, such as the gas or liquid phase.	https://doi.org/10.1016/j.jenvman.2023.119964	Sewage sludge; Pyrolysis; Process parameters; Biochar; Micropollutants

Municipal Biosolids (Sludge) PFAS Treatment Literature

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
December 2, 2023	Per- and polyfluoroalkyl substances (PFAS) in Canadian municipal wastewater and biosolids: Recent patterns and time trends 2009 to 2021	Sarah B. Gewurtz, Alexandra S. Auyeung, Amila O. De Silva, Steven Teslic, Shirley Anne Smyth	Science of The Total Environment	The concentrations of per- and polyfluoroalkyl substances (PFAS) were determined in raw influent, final effluent, and treated biosolids at Canadian wastewater treatment plants (WWTPs) to evaluate the fate of PFAS through liquid and solids trains of typical treatment process types used in Canada and to assess time trends of PFAS in wastewater between 2009 and 2021. Data for 42 PFAS in samples collected from 27 WWTP across Canada were used to assess current concentrations and 48 WWTPs were included in the time trends analysis. Although regulated and phased-out of production by industry since the early 2000s and late 2000s/early2010s, respectively, perfluorooctanesulfonate (PFOS), perfluorooctanoate (PFOA), and other long-chain PFAS continue to be widely detected in Canadian wastewater and biosolids. Short-chain PFAS that are not currently regulated in Canada were also widely detected. In general, elevated concentrations of several PFAS were observed at WWTPs that receive landfill leachate. Except for PFOS, concentrations of long-chain perfluoroalkyl carboxylates (PFCAs) and perfluoroalkane sulfonates (PFSAs) generally decreased over time in influent, effluent, and biosolids, which is attributable to industrial production phase-outs and regulations. Concentrations of PFOS did not decrease over time in wastewater media. This indicates that regulatory action and industrial phase-outs of PFOS are slow to be reflected in wastewater. Concentrations of short-chain PFCAs in wastewater influent and effluent consistently increased between 2009 and 2021, which reflect the use of short-chain PFAS as replacements for phased-out and regulated longer-chained PFAS. Short-chain PFAS were infrequently detected in biosolids. Continued periodic monitoring of PFAS in wastewater matrices in Canada and throughout the world is recommended to track the effectiveness of regulatory actions, particularly activities to address the broad class of PFAS.	https://doi.org/10.1016/j.scitotenv.2023.168638	Per- and polyfluoroalkyl substances (PFAS); Wastewater treatment plants (WWTPs); Transformation; Industrial production phase-outs and regulations; Influent and effluent; Biosolids
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://doi.org/10.1016/j.watres.2013.10.067	Drinking Water Treatment; Drinking Water Treatment Residuals; Sludge; PFAS Fate and Transport; PFAS adsortion; 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	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://doi.org/10.1016/j.jhazmat.2023.132734	Land application; PFAA; PFOS; Sewage sludge; Sulfonamide
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://doi.org/10.1016/j.jhazmat.2023.132734	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://doi.org/10.1116/6.0003104	N/A

Municipal Biosolids (Sludge) PFAS Treatment Literature

Last Updated July 1, 2025

Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
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://doi.org/10.1002/jeq2.20511	Sludge; Biosolids; PFAS Fate and Transport;drinking water treatment sludge; evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation
September 7, 2023	Effective stabilization of per- and polyfluoroalkyl substances (PFAS) precursors in wastewater treatment sludge by surfactant-modified clay	Tao Jiang, Md. Nahid Pervez, Monica M. Quianes,Weilan Zhang, Vincenzo Naddeo, Yanna Liang	Chemosphere	The application of biosolids or treated sewage sludge containing per- and polyfluoroalkyl substances (PFAS) in agricultural lands and the disposal of sludge in landfills pose high risks to humans and the environment. Although PFAS precursors have not been regulated yet, their potential transformation to highly regulated perfluoroalkyl acids (PFAAs) may enable them to serve as a long-term source and make remediation of PFAAs a continuing task. Therefore, treating precursors in sewage sludge is even more, certainly not less, critical than treating or removing PFAAs. In this study, a green surfactant-modified clay sorbent was evaluated for its efficacy in stabilizing two representative PFAA precursors in sludge, e.g., N-ethyl perfluorooctane sulfonamido acetic acid (N-EtFOSAA) and 6:2 fluorotelomer sulfonic acid (6:2 FTSA), in comparison with unmodified clay and powdered activated carbon (PAC). Results showed N-EtFOSAA and 6:2 FTSA exhibited distinct adsorption behaviors in the sludge without sorbents due to their different physicochemical properties, such as hydrophobicity and functional groups. Among the three sorbents, the modified clay reduced the water leachability of N-EtFOSAA and 6:2 FTSA by 91.5% and 95.4%, respectively, compared to controls without amendments at the end of the experiment (47 days). Within the same duration, PAC decreased the water leachability of N-EtFOSAA and 6:2 FTSA by 60.6% and 37.3%, respectively. At the same time, the unmodified clay demonstrated a poor stabilization effect and even promoted the leaching of precursors. These findings suggested that the modified clay had the potential for stabilization of precursors, while negatively charged and/or hydrophilic sorbents, such as the unmodified clay, should be avoided in the stabilization process. These results could provide valuable information for developing effective amendments for stabilizing PFAS in sludge or biosolids. Future research should evaluate the long-term effect of the stabilization approach using actual sludge from wastewater treatment facilities.	https://doi.org/10.1016/j.chemosphere.2023.140081	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
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://doi.org/10.1116/6.0002796	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation; Maine; Long term land application

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
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://doi.org/10.1016/j.chemosphere.2023.139412	Drinking Water Treatment Residuals; Sludge; PFAS Fate and Transport; PFAS adsortion; Poly-aluminum chloride; PAC; Alum; hydrophobicity; biochar;
June 29, 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://doi.org/10.1016/j.hazl.2023.100079	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal
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://doi.org/10.1016/j.jenvman.2023.118185	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://doi.org/10.1016/j.jhazmat.2023.131447	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
April 19, 2023	Smouldering to treat PFAS in sewage sludge	T. Fournie, T. L. Rashwan, C. Switzer and J. I. Gerhard	Waste Management	Wastewater treatment plants are accumulation points for per- and polyfluoroalkyl substances (PFAS), and are threfore important facilities for PFAS treatment. This study explored using smouldering combustion to treat PFAS in sewage sludge. Base case experiments at the laboratory scale (LAB) used dried sludge mixed with sand. High moisture content (MC) LAB tests, 75% MC sludge by mass, explored impacts of MC on treatment and supplemented with granular activated carbon (GAC) to achieve sufficient temperatures for thermal destruction of PFAS. Additional LAB tests explored using calcium oxide (CaO) to support fluorine mineralization. Further tests performed at an oil-drum scale (DRUM) assessed scale on PFAS removal. Pre-treatment sludge and post-treatment ash samples from all tests were analyzed for 12 PFAS (2C-8C). Additional emissions samples were collected from all LAB tests and analyzed for 12 PFAS and hydrogen fluoride. Smouldering removed all monitored PFAS from DRUM tests, and 4-8 carbon chain length PFAS from LAB tests. For base case tests, PFOS and PFOA were completely removed from sludge; however, high contents in the emissions (79-94% of total PFAS by mass) showed volatilization without degradation. Smouldering high MC sludge at approximately 900 degrees C (30 g GAC/kg sand) improved PFAS degradation compared to treatment below 800 degrees C (<20 g GAC/kg sand). Addition of CaO before smouldering reduced PFAS content in emissions by 97-99% by mass; with minimal PFAS retained in the ash and minimal hydrofluoric acid (HF) production, as the fluorine from the PFAS was likely mineralized in the ash. Co-smouldering with CaO had dual benefits of removing PFAS while minimizing other hazardous emission by-products.	https://doi.org/10.1016/j.wasman.2023.04.008	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
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://doi.org/10.1002/wer.10863	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid;
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	Per- and polyfluoroalkyl substances (PFAS) are persistent organic chemicals detected in biosolids worldwide, which have become a significant concern for biosolids applications due to their increasing environmental risks. Hence, it is pivotal to understand the magnitude of PFAS contamination in biosolids and implement effective technologies to reduce their contamination and prevent hazardous aftermaths. Thermal techniques such as pyrolysis, incineration and gasification, and biodegradation have been regarded as impactful solutions to degrade PFAS and transform biosolids into value-added products like biochar. These techniques can mineralize PFAS compounds under specific operating parameters, which can lead to unique degradation mechanisms and pathways. Understanding PFAS degradation mechanisms can pave the way to design the technology and to optimize the process conditions. Therefore, in this review, we aim to review and compare PFAS degradation mechanisms in thermal treatment like pyrolysis, incineration, gasification, smouldering combustion, hydrothermal liquefaction (HTL), and biodegradation. For instance, in biodegradation of perfluorooctane sulfonic acid (PFOS), firstly C-S bond cleavage occurs which is followed by hydroxylation, decarboxylation and defluorination reactions to form perfluoroheptanoic acid. In HTL, PFOS degradation is carried through OH-catalyzed series of nucleophilic substitution and decarboxylation reactions. In contrast, thermal PFOS degradation involves a three-step random-chain scission pathway. The first step includes C-S bond cleavage, followed by defluorination of perfluoroalkyl radical, and radical chain propagation reactions. Finally, the termination of chain propagation reactions produces very short-fluorinated units. We also highlighted important policies and strategies employed worldwide to curb PFAS contamination in biosolids.	https://doi.org/10.1016/j.jhazmat.2023.131212	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://doi.org/10.1016/j.scitotenv.2023.162357	Sludge; Biosolids; PFAS Fate and Transport;sludge; evaluation; PFAS Transformation; Sludge Incineration; Stack Emissions

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
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://doi.org/10.1016/j.watres.2023.119724	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://doi.org/10.1021/acs.est.2c06189	Sludge; Biosolids; PFAS Fate and Transport; diPAP precusor; evaluation; PFAS Transformation; Biosolids Treatment;
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://doi.org/10.1039/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://doi.org/10.1039/D2EM00350C	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; microbial degradation; microbes; PFAS partitioning

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
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://doi.org/10.1039/D2EW00677D	Sludge; Biosolids; PFAS Treatment; pyrolysis; Biochar; PFAS Removal; py-gas; py-liquid;
December 9, 2022	Incorporating hydrothermal liquefaction into wastewater treatment – Part II: Characterization, environmental impacts, and potential applications of hydrochar	Huan Liu, Nathalie Lyczko, Ange Nzihou, Cigdem Eskicioglu	Journal of Cleaner Production	Hydrothermal liquefaction (HTL) is a promising technique for renewable biofuel (biocrude) production from municipal sludge. However, its solid byproduct, hydrochar, requires sustainable management for further resource recovery and pollution control. This study comprehensively assessed the properties, environmental influences, and possible utilizations of hydrochar generated from mixed sludge (MS). With the increase of HTL reaction temperatures (290–360 °C) and residence time (0–30 min), the dry-weight contents of ash and fuel ratio increased from 10.5% and 0.1 in MS to 48.7–68.5% and 0.4–0.7 in hydrochar, respectively. However, the dry-basis contents of volatile matter, carbon, and higher heating value sharply decreased to 18.7–35.9%, 22.9–37.3%, and 8.6–16.0 MJ/kg, respectively. The leaching risks of inorganic contaminants from hydrochar were limited and controllable in various scenarios. Hydrochar performed more stable combustion than sludge, but its high ash contents and alkali index (0.28–0.72 kg/GJ) implied high risks of slagging and fouling. Hydrochar has a good potential for carbon sequestration due to low O/C ratios (<0.2) and improved recalcitrance index (0.43–0.48). Benefiting from intrinsic metals (e.g., Ca and Fe), catalytic hydrochar graphitization was feasible at a moderate temperature (1200 °C). Although hydrochar was restricted from land application for heavy metals accumulation, it is promising for metals and nutrient recovery. It has a total phosphorus (P) of 7.2–8.5% by weight, and thus P recovery is critical and necessary for mitigating environmental challenges and global P scarcity. Overall, this study contributed to the state-of-the-art in waste-to-resource development and cleaner production.	https://doi.org/10.1016/j.jclepro.2022.135398	PFAS Treatment; municipal sludge; hydrothermal liquefaction; biocrude; hydrochar metals recovery; nutrient recovery
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; supercritical water oxidation; pyrolysis; Incineration, Mineralization

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
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://doi.org/10.3390/pr10112187	PFAS Treatment; waste; Thermal Treatment; thermal treatment; sludge; biosolids; pyrolysis; py-gas
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 pyrolysis/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 organics 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 monitored due to its low regulated atmospheric discharge values. Alkali scrubbing is normally required to lower the HF concentration in the exhaust gas to acceptable discharge concentrations.	https://doi.org/10.1016/j.scitotenv.2022.158796	PFAS; Thermal treatment; Combustion; Pyrolysis; Biosolid
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 pyrolysis/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 organics 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 monitored due to its low regulated atmospheric discharge values. Alkali scrubbing is normally required to lower the HF concentration 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;

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
July 20, 2022	Per- and polyfluoroalkyl substances (PFAS) in sludge from wastewater treatment plants in Sweden - First findings of novel fluorinated copolymers in Europe including temporal analysis	Felicia Fredriksson, Ulrika Eriksson, Anna Kärrman, Leo W.Y. Yeung	Science of the Total Environment	Thousands of per- and polyfluoroalkyl substances (PFAS) are on the global market, while only a minor proportion is monitored regularly in the environment. Wastewater treatment plants (WWTPs) have been suggested to be a point source for PFAS to the environment due to emission of effluent and sludge. In this study, 81 PFAS including two rarely studied perfluoroalkyl sulfonamide-based (FASA) copolymers were analyzed in sludge samples to understand the usage of PFAS in the society. Sludge samples (n = 28) were collected at four WWTPs in Sweden between 2004 and 2017. The total levels of 79 measured PFAS were between 50 and 1124 ng/g d.w. All sludge samples showed detectable levels of both C8- and C4-FASA-based copolymers. The concentrations of the FASA-based copolymers were proposed to be reported in fluorinated side-chain equivalents (FSC eq.), in order to compare the levels of the copolymers with the other neutral and anionic PFAS, as no authentic standards were available. The concentrations of the FASA-based copolymers in sludge were between 1.4 and 22 ng FSC eq./g d.w. A general predomination of precursor and intermediate compounds was observed. A lower contribution of perfluoroalkyl carboxylic acids was noted for the WWTPs more influenced by domestic emission when compared with more influenced by industrial emission. An overall declining trend in the total PFAS concentration was seen between the years 2004 and 2017. The present study observed a shift from the C8-based chemistry toward shorter chain lengths, included a declining trend for C8-FASA-based copolymer over the entire study period. These findings further demonstrate the occurrence of side-chain fluorinated copolymers in Sweden and that sludge is a useful matrix to reflect the usage of PFAS in society and the potential for environmental exposure.	https://doi.org/10.1016/j.scitotenv.2022.157406	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
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://doi.org/10.1016/j.cej.2022.137838	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://doi.org/10.1007/s00216-022-04088-2	Sludge; Biosolids; PFAS Fate and Transport; diPAP precusor; evaluation; PFAS Transformation; Biosolids Treatment; plant uptake; bioaccumulation
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://doi.org/10.1016/j.hazadv.2022.100089	Sludge; biosolids, biochar, stabilization; incubation; Granulated activated carbon

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Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
April 1, 2022	Occurrence 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://doi.org/10.1039/D1EW00851J	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
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://doi.org/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://doi.org/10.1080/10962247.2021.2000903	PFAS Treatment; waste; electrochemical oxidation; gasification, supercritical water oxidation, pyrolysis;

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December 28, 2021	Hydrothermal liquefaction of sewage sludge – effect of four reagents on relevant parameters related to biocrude and PFAS	Weilan Zhang, Yanna Liang	Journal of Environmental Chemical Engineering	Catalytic hydrothermal liquefaction (HTL) can convert wet biomass into crude-like oil and has potential to degrade pollutants during the thermal depolymerization process. To avoid negative environmental impacts from per- and polyfluoroalkyl substances (PFAS) in sewage sludge after its final disposal, we comprehensively evaluated catalytic destruction of PFAS in sludge through HTL. The results showed that adding red mud to HTL was beneficial for the biocrude yield and significantly increased the carbon conversion efficiency and energy recovery of the hydrothermal process. HTL at 300 ◦C for 2 h degraded > 96% of spiked perfluorooctanoic acid (PFOA). The mass of spiked perfluorobutanesulfonic acid (PFBS) and perfluorooctanesulfonic acid (PFOS) and pre-existing perfluorohexanoic acid (PFHxA) and perfluoroheptanoic acid (PFHpA), however, increased in the HTL product streams. The remaining PFAS after HTL mainly stayed in the biocrude phase. Our findings indicated that HTL under the studied condition was not able to degrade all PFAS existed in sewage sludge. Although adding red mud could improve the HTL performance with respect to biocrude, this reagent did not improve the removal of perfluoroalkyl acids (PFAAs). As a matter of fact, the hydrothermal process amended with the selected reagents resulted in increased mass of PFBS, PFHxA, and PFHpA in the HTL products due to degradation of PFAA precursors. Thus, other treatment approaches for PFAS removal from sewage sludge need to be identified to prevent possible contamination of environments receiving PFAS-containing sludge.	https://doi.org/10.1016/j.jece.2021.107092	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
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; supercrital 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	Environmental Science: Processes & Impacts	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://doi.org/10.1039/D1EM00032B	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; New Hampshire; total oxidizable precursor assay PFAS partitioning
May 5, 2021	Effects of hydrothermal treatments on destruction of per- and polyfluoroalkyl substances in sewage sludge	Weilan Zhang, Yanna Liang	Environmental Pollution	Sewage sludge has become a sink of per- and polyfluoroalkyl substances (PFAS) due to the ineffectiveness of PFAS removal during conventional activated sludge treatment process. In this study, we evaluated the performance of an enhanced method for PFAS extraction from sewage sludge. Significant matrix effect was observed for samples derived from untreated and hydrothermally treated sludge. Extra steps for removing potential interferences were thus needed to reduce these matrix effects and improve the accuracy of PFAS quantification. Hydrothermal treatment at 165 degrees C for 0.5/2 h and 250 degrees C for 0.5 h increased the concentration of extractable PFAAs in treated sludge. Increasing the temperature to 300 degrees C resulted in complete degradation of PFCAs after hydrothermal processing, but still increased the concentrations of PFSAs and PFAA precursors. The concentration increase could be due to the conversion of PFAA precursors to PFAAs and the release of PFAAs from sewage sludge during thermal treatment. Ca(OH)(2) addition to hydrothermal treatment completely removed PFAA precursors but significantly increased the extractable PFAAs, except PFHpA and PFHxS, at 165 degrees C and all PFSAs at 300 degrees C. This study revealed the difficulties in extracting and quantifying PFAS in sludge and demonstrated the need for further research on finding suitable solutions for complete removal or destruction of PFAS in highly heterogeneous sewage sludge.	https://doi.org/10.1016/j.envpol.2021.117276	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment

Municipal Biosolids (Sludge) PFAS Treatment Literature

Last Updated July 1, 2025

Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
January 20, 2021	Linking PFAS partitioning behavior in sewage solids to the solid characteristics, solution chemistry, and treatment processes	Farshad Ebrahimi, Asa J. Lewis, Christopher M. Sales, Rominder Suri, Erica R. McKenzie	Chemosphere	Per- and polyfluoroalkyl substances (PFAS) have gained increasing attention due to the potential health risks that they present. Secondary sludge and biosolids are known as notable PFAS emission routes to the environment. In this study, partitioning behavior of 14 PFAS were investigated across four secondary wastewater treatment types (activated sludge, trickling filter, biological nutrient removal, and rotating biological contactor; n = 10) and three sludge stabilization methods (composting, aerobic digestion, and anaerobic digestion; n = 6). Batch experiments were conducted to evaluate how PFAS sorption to secondary sludge and biosolid was affected by various treatment methods, solid properties, and solution chemistry parameters. Insignificant differences in compound-specific partitioning coefficients (K(d)) were observed among the four secondary treatment methods. However, sludge stabilization resulted in significantly different partitioning behavior among biosolid samples, in which anaerobically digested biosolids generally had significantly higher K(d) values compared to aerobically digested and composted biosolids (anaerobic digestion > aerobic digestion > composting). Multiple linear regression models were developed to explain analyte-specific K(d) values across the biosolid samples and identified that solid-specific property significance was as follows: protein fraction > organic matter fraction > lipid fraction. Stabilization generally decreased the PFAS sorption capacity relative to the secondary sludge samples. Furthermore, PFAS K(d) increased with elevated calcium concentrations and ionic strengths and decreased with increasing pH values in sludge and biosolid samples. These findings could inform the decision-making process to reduce the release of PFAS to the environment.	https://doi.org/10.1016/j.chemosphere.2020.129530	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment
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://doi.org/10.1039/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 30, 2020	Removal and formation of perfluoroalkyl substances in Canadian sludge treatment systems - A mass balance approach	Narasimman Lakshminarasimman, Sarah B. Gewurtz, Wayne J. Parker, Shirley Anne Smyth	Science of the Total Environment	Poly- and per-fluoroalkyl substances (PFAS) are an emerging class of anthropogenic contaminants whose occurrence has raised concerns with the beneficial reuse of biosolids from wastewater treatment. This study evaluated the behavior of thirteen PFAS in nine Canadian sludge treatment systems including pelletization, alkaline stabilization, aerobic and anaerobic digestion processes. The composition of the overall PFAS-fluorine (SigmaPFAS-F) loading in a system fed with only primary sludge was dominated by perfluorodecanoate (PFDA), whereas systems with blended primary and waste activated sludge feeds had a mix of short and long chain PFAS in raw sludges and treated biosolids. An increase in average SigmaPFAS-F mass flow was observed through pelletization (19% formation) and alkaline stabilization (99% formation) processes indicating negative removal or contaminant formation. One of the two aerobic digestion systems and three of the five anaerobic digestion systems showed modest reductions (< 40% removal) in SigmaPFAS-F loading. Long chain PFAS such as perfluorodecanoate (PFDA) and perfluorooctane sulfonate (PFOS) exhibited a wide variation in behavior ranging from substantial formation (> 75% formation) to modest removal (42% removal) in the surveyed systems while short chain perfluoropentanoate (PFPeA) mass flows increased through the three systems where they occurred. Overall, the contaminant mass balances revealed that there were significant changes in mass flows of the target PFAS through all kinds of sludge treatment systems. The results of this study on PFAS fate through sludge processing can inform future global PFAS risk management activities as well as sludge treatment considerations.	https://doi.org/10.1016/j.scitotenv.2020.142431	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment

Municipal Biosolids (Sludge) PFAS Treatment Literature

Last Updated July 1, 2025

Publication Date*	Title	Authors	Journal	Abstract	Link	Key Words
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://doi.org/10.1016/j.chemosphere.2020.128018	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://doi.org/10.1039/C9EW01139K	Sludge; Biosolids; Hydrothermal Liquefaction (HTL); biofuel; biocrude oil; PFAS minerialization;
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://doi.org/10.1016/j.jhazmat.2013.03.016	Sludge; Biosolids; PFAS Fate and Transport; PFAS evaluation; PFAS Transformation; Biosolids Treatment; National Survey; PFAS partitioning
**Publication date reported is the earliest available date unless a specific "Version of Record" was noted.*						