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Freiburg, January 2023

Sewage Sludge as feedstock for pyrolysis to be included in the scope of the EU Fertilizing Products Regulation

Update of the EBI Position Paper elaborated in March 2020

The treatment of sewage sludge by pyrolysis offers great potential for the removal of many pollutants of high ecological and human health impact, as well as for the production of a highly valuable phosphorus fertilizer with a net positive effect on the climate.

In the EU Fertilizing Products Regulation[1] sewage sludge was excluded from the list of eligible feedstocks for pyrolysis & gasification materials to be used in agriculture. The reason was uncertainty whether contaminants of emerging concern are eliminated1. However, Article 42 of the EU Fertilizing Products Regulation outlines the possibility of amending Annexes I to IV in order to align them to technical progress and scientific evidence. Accordingly, the 2019 JRC Report on STRUBIAS materials states that the "proposal to exclude sewage sludge from the eligible input material list for CMC pyrolysis & gasification materials could possibly be revised once robust and extensive techno-scientific evidence underpins the safe use of (specific) pyrolysis & gasification materials derived from sewage sludge"[2].

To address the mentioned concerns, this paper presents the latest scientific evidence on the elimination of the most important contaminants in sewage sludges, including pathogens, organic pollutants, PFAS, PAHs and microplastics. It also addresses further benefits regarding climate and the direct yield of high-quality phosphorous fertilizers.

1 "At present, very few research results are available on the behaviour during the pyrolysis/gasification process of the many organic contaminants [...] that are possibly present in sewage sludge***"; "***Based on the precautionary principle and in view of the broad list of emerging contaminants in human-derived waste streams it is justified to exclude highly contaminated feedstocks (e.g. sewage sludge [...]) from the positive input material list to ensure human health and environmental safety"[2]

Pyrolysis destroys feedstock pathogens

Sewage sludge originates mainly from human excrements. Naturally, the sludge contains spores, pathogens, and pyrogens, which are of public health concern.[3] Standard hygienization of sewage sludge (e.g. heating of the sludge to 70 °C), does not eliminate all these contaminants.

The process conditions of pyrolysis (> 350 °C for several minutes) are much harsher even than approved sterilization conditions.[2] Accordingly, pyrolysis eliminates all pathogens[4] and pyrogens contained in sewage sludge – including bacteria, fungi, vira, spores, parasites, antibiotic resistance genes etc.[3] The final product, i.e. the biochar, is free of threats for public health.

Pyrolysis

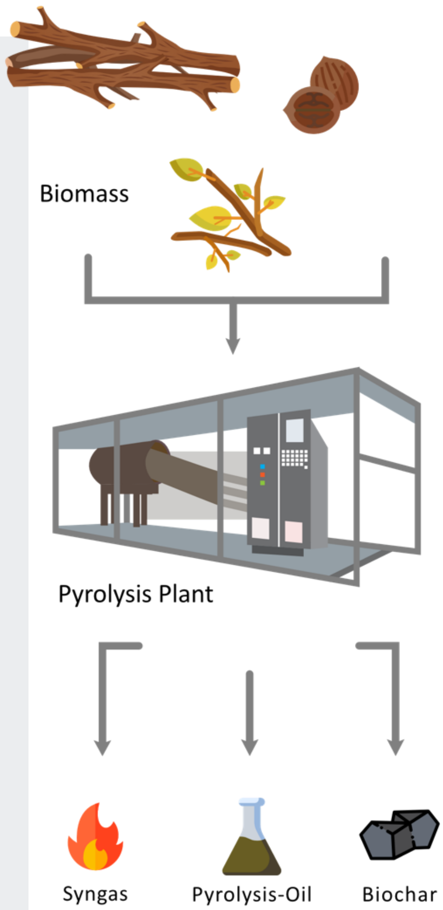
The heating of biomass in a low-oxygen environment is called pyrolysis and converts organic carbon into pyrolysis gas and fixed/elemental carbon. While the natural degradation of organic carbon leads to the release of greenhouse gases like CO2 or CH4 into the atmosphere, fixed carbon is extremely durable. Unless it is burned, it resists weathering/degradation and remains stable for centuries.[5][6][7]

If the fixed carbon remains in the soil or is used in other long-lasting material applications, **it can be considered as a permanent carbon sink** (Pyrolytic Carbon Capture and Storage (PyCCS)).

Biochar

A main product of the pyrolysis of biomass is biochar. Biochar is a porous, carbonaceous material with a broad range of applications where the contained carbon remains stored as a long-term carbon sink.

The biochar can be used in agriculture or the production of climate-friendly polymers, in materials for the construction industry or replace fossil carbon in industrial manufacturing.



[2] Requiring 132 °C for 4 minutes with steam (see CDC Steam Sterilization Disinfection & Sterilization Guidelines) and 250 °C to remove pyrogens (bacterial endotoxins) under dry conditions (Dry Heat Sterilization)
[3] See "Annex: Studies regarding contaminants elimination"

Sewage treatment plant - by Ivan Bandura, Unsplash

Pyrolysis eliminates micropollutants from sewage sludge

Increasing concern is raised regarding the spreading of sewage sludge on farmland, due to the presence of micropollutants in sludges. Recent scientific research has demonstrated that pyrolysis will destroy or remove several types of micropollutants:

- **Organic pollutants** (e.g. pharmaceuticals, hormone disrupting molecules): Scientific evidence shows that at sufficiently high pyrolysis temperatures (> 500 °C) and long durations (> 3 min), all reference organic contaminants and micropollutants were completely or nearly completely degraded or driven off the solid material. A study published in 2019 by the German Ministry of Environment (Bundesumweltamt)[8] analyzed the residues of various pharmaceutical biosolids after pyrolytic treatment above 500 °C. After the process, all of the investigated pharmaceuticals were below the detection limit. The authors conclude: ***“With thermo-chemical treatments (i.e. pyrolysis) a complete destruction of the pharmaceutical residues is achieved. No further technical treatment measures are necessary.”*** Find an elaborate list of studies supporting the elimination of organic pollutants annexed to this paper.

- **PFAS**: Per- and Polyfluoroalkyl Substances (PFAS) are eliminated by the process of pyrolysis. Kundu et al. (2021)[9] found that > 90 % of PFOS and PFOA in sewage sludge were destroyed in a pyrolysis-combustion integrated process. Evidence from the US EPA Office of Research and Development (2021)[10] carried out on the US-based company Bioforcetech’s commercially installed pyrolysis plant shows that pyrolysis at 600 °C for 10 minutes and combustion of pyrolysis gases at 850 °C eliminate PFAS from sewage sludge. Bioforcetech (2021)[11] has reported **38 PFAS compounds that were all kept at or removed to below detection limit in the biochar** in their pyrolysis and pyrolysis gas burning process. At the Fårevejle wastewater treatment plant in Denmark, sewage sludge pyrolysis at a temperature of 650 °C and a residence time of more than 3 minutes has showed to eliminate all 7 PFAS compounds previously detected in the feedstock.[12]

- **PAH**: Spreading sewage sludge on agricultural land is very common in Europe, although sludges potentially contain elevated levels of toxic polycyclic aromatic hydrocarbons (PAH). Properly designed pyrolysis processes can eliminate these chemical compounds, resulting in biochar with a PAH content below limit values or even detection limits: Moško et al. (2021)[13] demonstrated that slow pyrolysis at > 400 °C removes more than 99.8 % of the studied PCB, PAH, endocrine-disrupting chemicals, and hormonal compounds. The authors state: ***“High temperature (> 600 °C) slow pyrolysis can satisfactory remove organic pollutants from the resulting sludge-char, which could be safely applied as soil improver”***[4].

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[4] At the Fårevejle wastewater treatment plant in Denmark, a sewage sludge biochar without detectable DEHP, alkylphenols and –ethoxylates, LAS and a total of 9 PAH compounds at 0,2 mg/kg in the dry matter is obtained through a pyrolysis process at 650 °C with a residence time of more than 3 minutes.[12]

Pyrolysis eliminates microplastic from sewage sludge

Research indicates that sewage sludge is a sink for microplastic. Thus, effective reduction of the plastic fragments is critical for potential dispersal.[14] Ni et al. (2020)[15] found that ***"Polyethylene and polypropylene, the two most abundant microplastics in sewage sludge, were entirely degraded when the pyrolysis temperature reached 450 °C."*** Total concentrations of microplastic were reduced from 550.8 - 960.9 to 1.4 - 2.3 particles/g at pyrolysis temperatures of 500 °C. No microplastic with a particle size of 10-50 µm remained.

To illustrate the behavior of plastic during high temperature treatment (for example during pyrolysis), the thermal decomposition curves of PE and PP are shown in *Figure 1*. PE and PP thermal degradation shows a dramatic mass loss between 400 °C and 500 °C, while above 500 °C *"the material degraded completely without leaving any noticeable residue."[16]* PET, a highly relevant plastic type regarding sewage sludge, starts to decompose at a temperature above 450 °C and transitions to the gas phase.[5] PET decomposition is terminated in less than one minute (α = 1) at temperatures above 500 °C[23]. The cracked gases are of high calorific value and can be used for energy production. Thus, **the pyrolysis of sewage sludge is a good method to drastically reduce microplastic in the environment**.

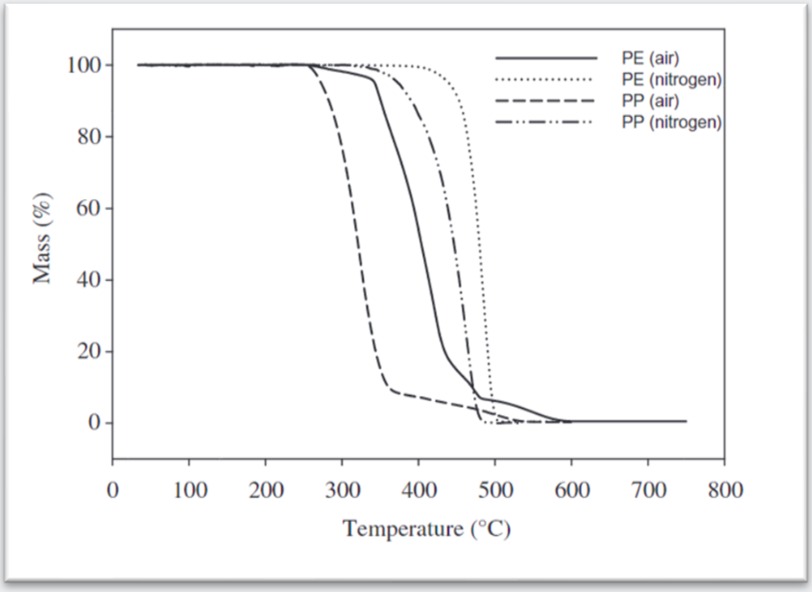


Figure 1: TG scans of PE and PP measured at a constant heating rate in two different test environments: inert atmosphere and in air.[16]

[5] See *Figure 3* in the Annex under "Studies regarding contaminants elimination"

Biochar contribution to carbon sinks and GHG emission reduction in agriculture

Pyrolysis of sewage sludge can make a significant contribution to mitigating climate change. Containing approximately 25% of stable carbon, the char resulting from the process acts as a permanent carbon sink if used in agriculture. **Between 300 and 500 kg CO_2 could be stored for each ton of dried sludge**. Furthermore, storing and spreading sewage sludge directly on farmland significantly contributes to greenhouse gas (CH_4 and N_2O) emissions.[17] According to a life cycle assessment of the Technical University of Denmark, drying and pyrolyzing sewage sludge could reduce greenhouse gas emissions in the order of 1000-1700 kg of CO_2-eq per ton of dried sludge[18] with respect to 6 months storage of sewage sludge and direct field application, calculating CO2 emissions for 100 years.

Biochar from Sewage Sludge as p-fertilizer

An increasing number of EU member states must recover and recycle phosphorus from sewage sludge for soil fertilization. Various methods are available, but pyrolysis at temperatures from 500 to 800 °C is the most carbon efficient. Pyrolysis leads to a product that can be used as fertilizer without further chemical extraction. The availability of P_2O_5 in the biochar from sludges is up to 80 %, measured in ammonium citrate.[21] According to Kratz and Schnug (2009)[22], this indicates a highly valuable fertilizer.

Sewage Sludge pyrolysis yields a carbon negative p-fertilizer

In 2019, the German Federal Environmental Agency published a comparative study of phosphate fertilizers in Germany, including conventional products and respective recycled phosphates[19]. According to the publication, the current consumption of non-renewable resources for phosphate fertilizing products results in emissions of around 1,2 kg CO_2 eq/kg P_2O_5.[19] The study emphasizes the high importance of valorizing recycled biosolids products. The pyrolysis of sewage sludge has a high potential to mitigate the environmental impact and global warming caused by fertilizers.[20] A calculation performed by PYREG supports this assumption: Biochar from sewage sludge can obtain a GWP of -4,01 kg CO_2 eq/ kg P_2O_5 (*Figure 2*).

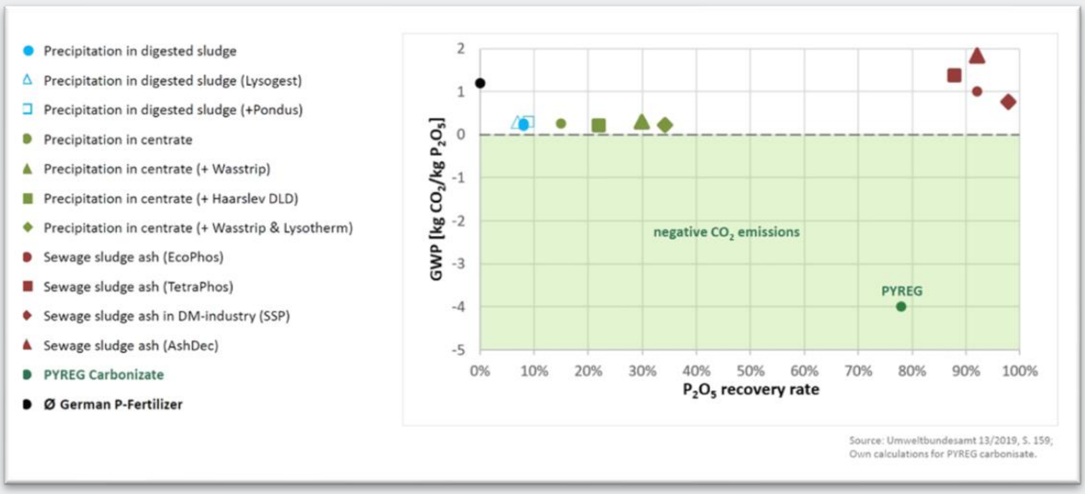
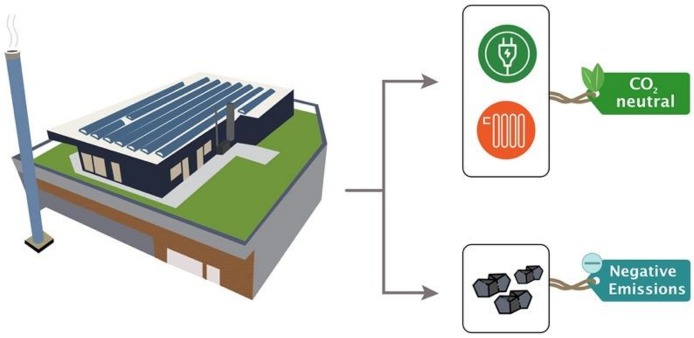


Figure 2: Diagram on Pyreg's calculation: GWP and P recovery rates comparing common fertilizers, other P-recovery solutions and Pyreg's biochar.

Sewage Sludge pyrolysis is deployable and scalable

Sewage sludge pyrolysis is already a mature technology with several suppliers who have reached TRL8 (demonstration plant) or 9 (industrial plant). For instance, some industrial plants are currently in continuous operation in Germany and Czech Republic, under commission in Denmark, while demonstration plants have been operated successfully in Sweden, Germany, Italy and USA. Most of those plants work in the range of 0.5 t/h to 1 t/h of dewatered sludge (per process line), equivalent to a plant serving 50,000 PE to 200,000 PE. Therefore, they are perfectly compatible with a decentralized model, where the sludge pyrolysis is/ can be directly installed on the wastewater treatment site. Higher treatment capacities can be achieved by installing several modules in parallel.

Sludge drying is required prior to pyrolysis, but most of the pyrolysis units combine a preliminary drying machine and a heat recovery system that transfers heat to the drying step. In most cases, the combination of drying and pyrolysis is energy self-sufficient: the energy recovered from the pyrolysis gas is sufficient to dry all the sludge. As no additional gas or fuel is required, the **system can operate in full autonomy - without consuming fossil fuel and thus without emitting fossil CO_2**.



Environmentally friendly production of biochar with an up to four-fold value creation: (i) generation of CO2- neutral electricity, (ii) CO2-neutral heat, (iii) biochar and (iv) negative emissions. Plant types that are not designed for electricity generation convert a higher proportion of the initial biomass into biochar and thus into carbon sinks.

References:

[1]. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003; Commission Delegated Regulation of 2021-07-07 amending Annexes II, III and IV to regulation (EU) No 2019/1009 for the purpose of adding pyrolysis and gasification materials as a component material category in EU fertilizing products. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R2088

[2]. Huygens, D., Saveyn, H., Tonini, D., Eder, P. and Delgado Sancho, L., Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009), EUR 29841 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09887-4, doi:10.2760/551387, JRC117856. https://publications.jrc.ec.europa.eu/repository/handle/JRC117856

[3]. Huygens, D., Garcia-Gutierrez, P., Orveillon, G., Schillaci, C., Delre, A., Orgiazzi, A., Wojda, P., Tonini, D., Egle, L., Jones, A., Pistocchi, A. and Lugato, E., Screening risk assessment of organic pollutants and environmental impacts from sewage sludge management, EUR 31238 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-57322-7 (online), doi:10.2760/541579 (online), JRC129690.

[4]. Paz-Ferreiro, Jorge, Aurora Nieto, Ana Méndez, Matthew Peter James Askeland, and Gabriel Gascó. 2018. "Biochar from Biosolids Pyrolysis: A Review" International Journal of Environmental Research and Public Health 15, no. 5: 956. https://doi.org/10.3390/ijerph15050956

[5]. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, IPCC. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, S. (eds). Published: IPCC, Switzerland.

[6]. Lehmann, Johannes & Abiven, Samuel & Kleber, Markus & Pan, Gen-Xing & Singh, Bhupinder Pal & Sohi, Saran & Zimmerman, Andrew. (2015). Persistence of biochar in soil. Biochar for Environmental Management: Science, Technology and Implementation. 235-282.

[7]. Wang, J., Xiong, Z., and Kuzyakov, Y. (2016). Biochar stability in soil: meta-analysis of decomposition and priming effects. Global Change Biology - Bioenergy 8(3), S. 512-523.

[8]. Bundesumweltamt (2019) Arzneimittelrückstände in Rezyklaten der Phosphorrückgewinnung aus Klärschlämmen, Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit, Forschungskennzahl 3715 33 401 0, UBA-FB 002724 (https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-03-29_texte_31-2019_arzneimittelrueckstaende-klaerschlamm_v2.pdf)

[9]. Kundu, S., Patel, S., Halder, P., Patel, T., Marybali, M. H., Pramanik, B. K., Praz-Ferreiro, J., Figueiredo, C. C., Bergmann, D., Surapaneni, A., Megharaj, M., Shah, K., Removal of PFASs from biosolids using a semi-pilot scale pyrolysis reactor and the application of biosolids derived biochar for the removal of PFASs from contaminated water, Environ. Sci.: Water Res. Technol., 2021, 7, 638–649

[10]. Gullet, B., EPA PFAS innovative treatment team (PITT) findings on PFAS destruction technologies, EPA Tools & Resources Webinar February 17, 2021

[11]. https://ccag.ca.gov/wp-content/uploads/2020/02/BFT_FEB_2020-1.pdf

[12]. Sampling 28-06-2022, Eurofins Miljø og Vand A/S analytical reports AR-22-CA-22073400-01, AR-22-CA-22073409-01

[13]. Moško J, Pohořelý M, Cajthaml T, Jeremiáš M, Robles-Aguilar AA, Skoblia S, Beňo Z, Innemanová P, Linhartová L, Michalíková K, Meers E. Effect of pyrolysis temperature on removal of organic pollutants present in anaerobically stabilized sewage sludge. Chemosphere. 2021 Feb;265:129082. doi: 10.1016/j.chemosphere.2020.129082. Epub 2020 Nov 23. PMID:

33309446.

[14]. Charles Rolsky, Varun Kelkar, Erin Driver, Rolf U. Halden, Municipal sewage sludge as a source of microplastics in the environment, Current Opinion in Environmental Science & Health, Volume 14, 2020, Pages 16-22, ISSN 2468-5844, https://doi.org/10.1016/j.coesh.2019.12.001.

[15]. Ni, B., Zhu, Z., Li, W., Yan, X., Wei, W., Xu, Q., Xia, Z., Dai, X., & Sun, J. (2020). Microplastics Mitigation in Sewage Sludge through Pyrolysis: The Role of Pyrolysis Temperature. Environmental Science and Technology Letters, 7, 961-967.

[16]. Sudip Ray, Ralph P. Cooney, chapter 9 – Thermal degradation of polymer and polymer composites, Myer Kutz, Handbook of environmental degradation of materials (third edition), william Andrew publishing, 2018, pp. 185-206, https://doi.org/10.1016/B978-0-323-52472-8.00009-5

[17]. Lars Elsgaard (ed.), Anders Peter S. Adamsen, Henrik B. Møller, Anne Winding, Uffe Jørgensen, Esben Ø. Mortensen, Emmanuel Arthur, Diego Abalos, Mathias N. Andersen, Henrik Thers, Peter Sørensen , Addisu Anteneh Dilnessa, Katarina Elofsson, "Knowledge synthesis on biochar in Danish agriculture - Biochar production, use and effect in soil agroecosystems (part 1) and Economic assessment of biochar production and use (part 2)", Advisory report from DCA No. 208 – Danish Centre for Food and Agriculture, 2022

[18]. Tobias Pape Thomsen, Technical University of Denmark, 2018, AquaGreen PCP phase 2, WP 5 Final report: Drying and pyrolysis of sludge – in a climate perspective.

[19]. Fabian Kraus, Malte Zamzow, Lea Conzelmann, Christian Remy, Anne Kleyböcker, Wolfgang Seis, Ulf Miehe, Kompetenzzentrum Wasser Berlin gGmbH, Ludwig Hermann, Ralf Hermann, Proman Management GmbH, Christian Kabbe, UBA TEXTE 13/2019, Ökobilanzieller Vergleich der P-Rückgewinnung aus dem Abwasserstrom mit der Düngemittelproduktion aus Rohphosphaten unter Einbeziehung von Umweltfolgeschäden und deren Vermeidung, 2019, Umweltbundesamt, ISSN 1862-4804.

[20]. Ghorbani, M.; Konvalina, P.; Walkiewicz, A.; Neugschwandtner, R.W.; Kopecký, M.; Zamanian, K.; Chen, W.-H.; Bucur, D. Feasibility of Biochar Derived from Sewage Sludge to Promote Sustainable Agriculture and Mitigate GHG Emissions—A Review. Int. J. Environ. Res. Public Health 2022, 19, 12983. https://doi.org/10.3390/ijerph191912983

[21]. Deutsche Gesellschaft für Abfallwirtschaft e.V., 5. Wissenschaftskongress Abfall- und Ressourcenwirtschaft am 19. und 20. März 2015 an der Universität Innsbruck Kevin Friedrich, Katharina Schuh, Thomas Appel Trockene Klärschlammkarbonisierung – ist ein dezentrales Phosphorrecycling möglich?

[22]. Kratz, S.; Schnug, E., 2009. On the solubility and plant availability of phosphorus from mineral fertilizers – a review, Journal für Kulturpflanzen, 61 (1). S. 2–8, 2009, ISSN 0027-7479 Verlag Eugen Ulmer KG, Stuttgart

[23]. Osman, A.I., Farrell, C., Al-Muhtaseb, A.H. et al. Pyrolysis kinetic modelling of abundant plastic waste (PET) and in-situ emission monitoring. Environ Sci Eur 32, 112 (2020). https://doi.org/10.1186/s12302-020-00390-x https://www.researchgate.net/figure/Reaction-progress-a-versus-the-temperature-for-the-PET-pyrolysis-where-the-coloured-and_fig1_343994995.

[24]. US EPA Research brief January 2021, Potential PFAS destruction technology: Pyrolysis and gasification.

[25]. EPA PFAS innovative treatment team (PITT) findings on PFAS destruction technologies, EPA Tools & Resources Webinar February 17, 2021, Gullett B.

[26]. Thoma E. D. et. al., Pyrolysis processing of PFAS-impacted biosolids, a pilot study, Journal of the Air & Waste Management Association, 2022, Vol 72, No. 4, 309-318

[27]. Thoma E. D. et. al., Pyrolysis processing of PFAS-impacted biosolids, a pilot study, Journal of the Air & Waste Management Association, 2022, Vol 72, No. 4, 309-318, Supplementary material, "SI Table 7. Summary of fluorinated compound canister analysis, acquired at LA"

[28]. Cerna, L. (2014). The Nature of Policy Change and Implementation: A Review of Different

Theoretical Approaches, Semantic Scholar, Corpus ID: 16297938

[29]. Hoffman, T. C., Zitomer, D. H., & McNamara, P. J. (2016). Pyrolysis of wastewater biosolids significantly reduces estrogenicity. Journal of Hazardous Materials, 317, 579–584. https://doi.org/10.1016/j.jhazmat.2016.05.088

[30]. Ross, J. J., Zitomer, D. H., Miller, T. R., Weirich, C. A., & McNamara, P. J. (2016). Emerging investigators series: Pyrolysis removes common microconstituents triclocarban, triclosan, and nonylphenol from biosolids. Environmental Science: Water Research and Technology, 2(2), 282–289. https://doi.org/10.1039/c5ew00229j

[31]. Zielińska, A., & Oleszczuk, P. (2015). Evaluation of sewage sludge and slow pyrolyzed sewage sludge-derived biochar for adsorption of phenanthrene and pyrene. Bioresource Technology, 192, 618–626. https://doi.org/10.1016/J.BIORTECH.2015.06.032

[32]. Biswal, D. R., & Singh, R. P. (2004). Characterisation of carboxymethyl cellulose and polyacrylamide graft copolymer. Carbohydrate Polymers, 57(4), 379–387. https://doi.org/10.1016/J.CARBPOL.2004.04.020

[33]. Dai, Q., Wen, J., Jiang, X., Dai, L., Jin, Y., Wang, F., Chi, Y., & Yan, J. (2018). Distribution of PCDD/Fs over the three product phases in wet sewage sludge pyrolysis. Journal of Analytical and Applied Pyrolysis, 133, 169–175. https://doi.org/10.1016/J.JAAP.2018.04.005

[34]. Kimbell, Lee & Kappell, Anthony & Mcnamara, Patrick. (2018). Effect of Pyrolysis on the Removal of Antibiotic Resistance Genes and Class I Integrons from Municipal Wastewater Biosolids. Environmental Science: Water Research & Technology. 4. 10.1039/C8EW00141C.

[35]. Frišták, V., Pipíška, M., & Soja, G. (2018). Pyrolysis treatment of sewage sludge: A promising way to produce phosphorus fertilizer. Journal of Cleaner Production, 172, 1772–1778. https://doi.org/10.1016/J.JCLEPRO.2017.12.015

[36]. Simón, M., García, I., Diez-Ortiz, M. et al. Biochar from Different Carbonaceous Waste Materials: Ecotoxicity and Effectiveness in the Sorption of Metal(loid)s. Water Air Soil Pollut 229, 224 (2018). https://doi.org/10.1007/s11270-018-3860-8

[37]. Paz-Ferreiro J, Nieto A, Méndez A, Askeland MPJ, Gascó G. Biochar from Biosolids Pyrolysis: A Review. Int J Environ Res Public Health. 2018 May 10;15(5):956. doi: 10.3390/ijerph15050956. PMID: 29748488; PMCID: PMC5981995.

[38]. Liu, Z., Singer, S., Tong, Y., Kimbell, L., Anderson, E., Hughes, M., Zitomer, D., & McNamara, P. (2018). Characteristics and applications of biochars derived from wastewater solids. Renewable and Sustainable Energy Reviews, 90, 650–664. https://doi.org/10.1016/J.RSER.2018.02.040

[39]. Figueiredo, C. C. de, Chagas, J. K. M., da Silva, J., & Paz-Ferreiro, J. (2019). Short-term effects of a sewage sludge biochar amendment on total and available heavy metal content of a tropical soil. Geoderma, 344, 31–39. https://doi.org/10.1016/J.GEODERMA.2019.01.052

[40]. Mierzwa-Hersztek M, Gondek K, Klimkowicz-Pawlas A, Baran A, Bajda T. Sewage sludge biochars management-Ecotoxicity, mobility of heavy metals, and soil microbial biomass. Environ Toxicol Chem. 2018 Apr;37(4):1197-1207. doi: 10.1002/etc.4045. Epub 2018 Feb 5. PMID: 29150956.

[41]. Gonzaga, M. I. S., de Souza, D. C. F., de Almeida, A. Q., Mackowiak, C., Lima, I. da S., Santos, J. C. de J., & de Andrade, R. S. (2019). Nitrogen and phosphorus uptake efficiency in indian mustard cultivated during three growth cycles in a copper contaminated soil treated with biochar. Ciencia Rural, 49(1). https://doi.org/10.1590/0103-8478cr20170592

[42]. Grutzmacher, P., Puga, A. P., Bibar, M. P. S., Coscione, A. R., Packer, A. P., & de Andrade, C. A. (2018). Carbon stability and mitigation of fertilizer induced N2O emissions in soil amended with biochar. Science of The Total Environment, 625, 1459–1466. https://doi.org/10.1016/J.SCITOTENV.2017.12.196

ANNEX: Studies regarding contaminants elimination

Studies regarding organic pollutants

(Hoffman *et al.*, 2016)[29] demonstrates that the pyrolytic treatment of biosolids at a temperature of 400 °C almost completely removed (> 95 %) estrogenic compounds associated with biosolids. The melting and boiling points of all common estrogens are below 260 °C and 440 °C, respectively. After the estrogenic compounds melt into the liquid phase, they will partition to the gas phase (away from the biochar) as the liquid-gas phase equilibrium is approached. These compounds will thus presumably have volatilized at pyrolysis temperatures of 500 °C. After initial volatilization from the biochar, the estrogenic compounds could either partition to the pyrolysis oil or pyrolysis gas or be transformed through thermal decomposition. The authors conclude: "*pyrolysis of biosolids can be used to produce a valuable soil amendment product, biochar,* ***that minimizes discharge of estrogens to the environment***."

(Ross *et al.*, 2016)[30] demonstrate that pyrolytic treatment at 500 °C removed after less than 5 minutes more than 90 % of microconstituents like the antibiotic triclocarban, the pharmaceutical conservation agent triclosan as well as the non-ionic tenside nonylphenol (to be found in pharmaceuticals, fungicides, paints etc.) from the solid residue. At 600 °C nonylphenol was even below the detection limit. Their fate studies revealed that microconstituents were both volatilized and thermochemically transformed during pyrolysis. Reductive dehalogenation products of triclocarban and suspected dehalogenation products of triclosan were identified in pyrolysis gas and would be completely degraded by the usual pyrogas combustion. The authors conclude: "***Application of biosolids-derived biochar to soil in place of biosolids has potential to minimize organic microconstituents discharged to the environment*** *provided appropriate management of pyrolysis gas and pyrolysis oil*" (the latter is usually co-combusted in sewage pyrolysis).
(Ross et al., 2016 was referenced by the STRUBIAS report but unfortunately to express the contrary of the paper's main message, i.e. "*the limitations of the potential of dry and wet pyrolysis/gasification processes to remove organic pollutants*" at lower temperatures than 500 °C).

A study published by the German Ministry of Environment in 2019 **(Bundesumweltamt 2019)** investigated pharmaceutical residues of various biosolids after pyrolytical treatments above 500 °C. The selected substances were Ciprofloxacin, Levofloxacin, Clarithromycin, Carbamazepin, 17-α-Ethinylestradiol, Diclofenac, Cefuroxim, Sulfamethoxazol, 17-β-Estradiol, Metoprolol and Bezafibrate. Following the pyrolysis treatment with operating temperatures above 500 °C all values of the investigated pharmaceuticals were below the detection limit. The authors concluded: With thermo-chemical treatments (i.e. pyrolysis) **a complete destruction of the pharmaceutical residues is achieved**. No further technical treatment measures are necessary.

(Zielińska & Oleszczuk, 2015)[31] found that the conversion of biosolids to biochar reduced total PAH content from 8 to 25-fold compared to the original biosolids.

(Biswal & Singh, 2004)[32] performed thermogravimetric analyses (TGA) of flocculants that are potentially used in wastewater treatment. These substances were effectively destroyed at 400 °C.

(Dai *et al.*, 2018)[33] evaluated the **fate of PCDD/Fs during sewage sludge pyrolysis**. PCDD/Fs were partially dechlorinated during pyrolysis, but the main factor determining their fate was distillation. Comparing sewage sludge char with the untreated sewage sludge, 98-99% of PCDD/Fs and about 90% of PCDD/Fs toxicity quantified in I-TEQ (International Toxicity Equivalent Quantity) were eliminated under relevant pyrolysis conditions (500-700 °C).

(Kimbell *et al.,* 2018)[34] showed that a pyrolysis of 5 minutes at 500 °C is sufficient to eliminate **all genes including antibiotic resistance genes below the detection limit.**

Pyrolysis reduces availability of polyaromatic hydrocarbons (PAHs): **(Fristak et al., 2018)**[35] showed that pyrolysis **can eliminate 90% of the total content of 16 EPA-PAH** of sewage sludge which is similar to the findings of other studies, e.g. Kong *et al.*, 2019 and the review of Liu *et al.*, 2018.[38]

(Simon *et. al.,* 2018)[36] performed **toxicity tests with enchytraeids** and found that **no harmful effects would be expected at application rates of sewage sludge char of ≤ 11.5 t ha^{-1}**. We expect that in praxis, application rates would not exceed 1-3 t ha^{-1}.

A review paper on "*Biochar from biosolids pyrolysis*" was published by **(Paz-Ferreiro *et al.*, 2018)**.[37] The paper convincingly shows the potential of various pyrolyzed biosolids to increase crop yield, enhance soil enzymatic activity, increase microbial biomass in soil, improve compost quality, reduce GHG emissions, reduce NH_4 and NO_3 leaching and to preserve most of the initial P (> 90%) in a plant available form. The authors conclude: "*Pyrolysis of biosolids leads to several benefits, compared to the traditional landfilling, incineration or land application. This includes few gaseous emissions, the destruction of pathogens, the potential to recover energy and a solid product, which can be used as a soil amendment. The nutrient content of biochars prepared from biosolids is high, in particular for phosphorus. Paradoxically, very limited work exists concerning the use of biosolids biochar as a product to improve agronomic performance. This could be due to **concerns of toxicity via the food chain, which seems irrational given the demonstrated ability of biochar to immobilize pollutants,** in particular heavy metals. The use of biochar for growing non-edible plants in horticulture, as a substitute for other growing media materials, could mitigate these concerns.*"

Another exhaustive review paper about the **characteristics and applications of biochars derived from wastewater solids** was published by **(Liu *et al.,* 2018)**.[38] The authors propose an integrated wastewater treatment process that produces and uses wastewater biochar for a variety of food, energy, and water (FEW) applications. The review paper provides a valuable overview about the general topic and confirm that all relevant organic pollutants are eliminated or reduced to an extend that the resulting materials can be applied without damaging the environment, the food chain or users.

A multitude of further studies demonstrated **agronomic benefits** of applying biochar made from biosolids, the following are a short selection of most relevant publications:

(de Figueiredo *et al.*, 2019)[39] found that sewage sludge chars produced at 300 and 500 °C increased the colonization of maize roots with arbuscular mycorrhiza fungi (AMF) and therefore **improve mutualistic symbiotic association of maize and AMF.**

(Mierzwa-Hersztek *et al.*, 2018)[40] found that sewage sludge char **increased the biomass production** in *Poa pratensis* by up to 100% compared to a non-amended control under lab conditions.

(Gonzaga *et al.*, 2019)[41] found **significantly increased biomass production** of Indian mustard over three years after sewage sludge char amendment to tropical soil.

(Grutzmacher *et al.*, 2018)[42] found that amendment with sewage sludge char **reduced fertilizer induced N_2O emissions by 87%** in a microcosm experiment.

Many studies are published regarding **heavy metals originated from the biosolid feedstock**. We do not summarize those here as the thresholds for heavy metals suggested by the STRUBIAS report would already assure that no heavy metal contamination could occur.

Study on PET thermal degradation

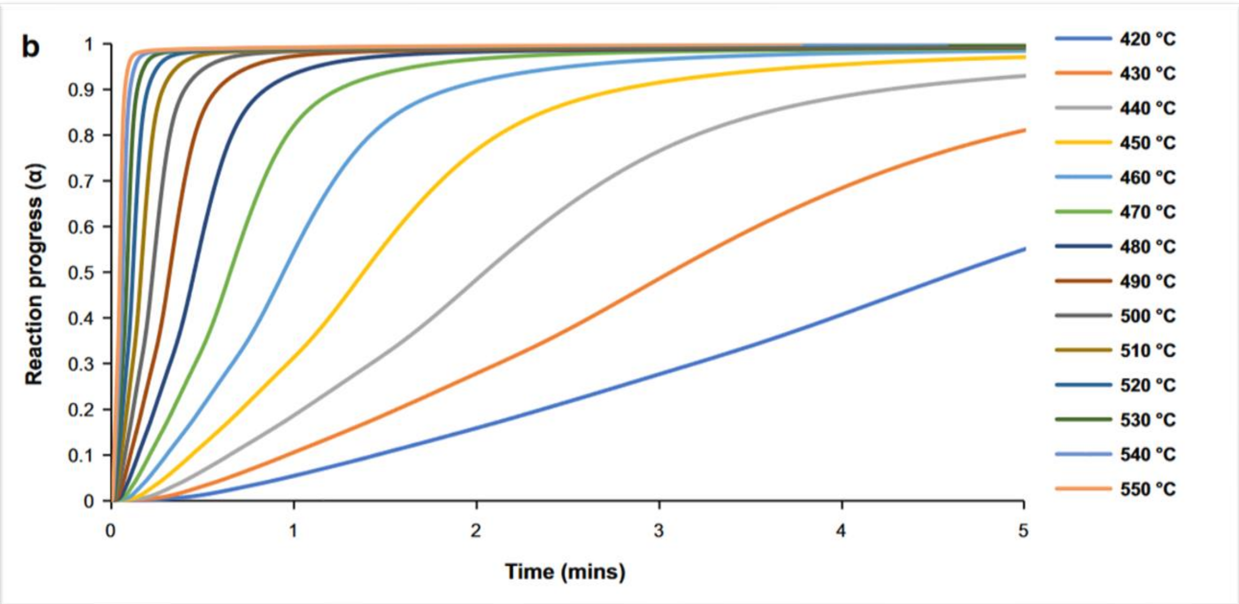
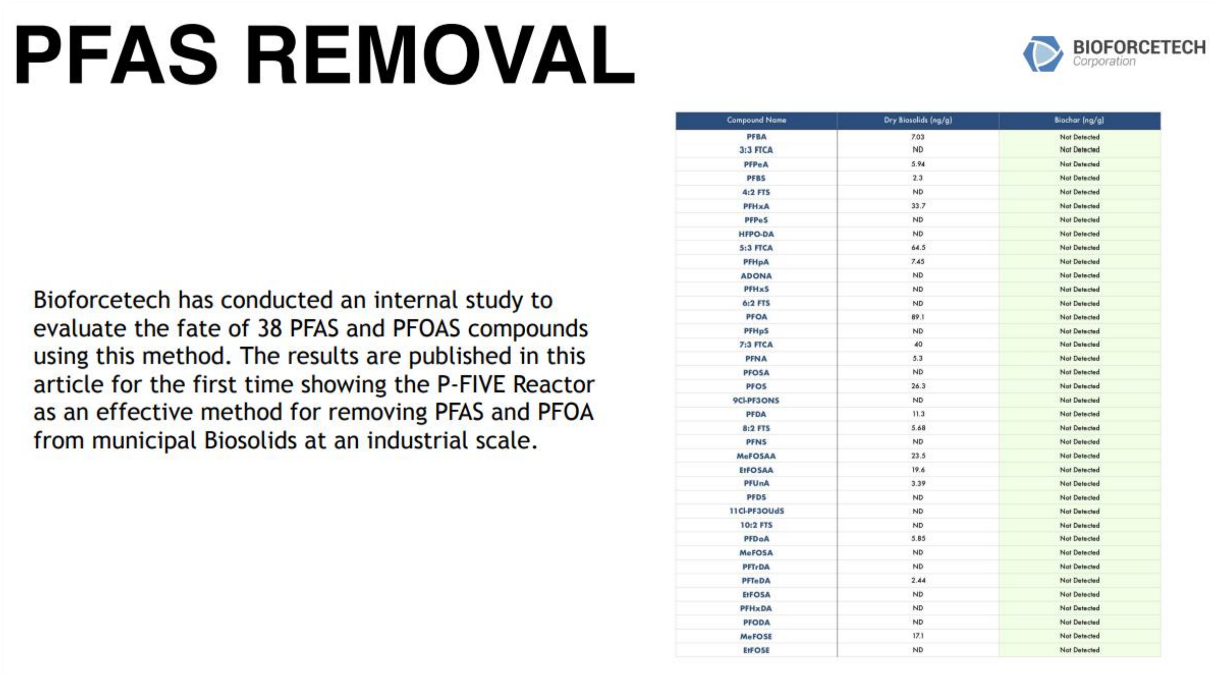


Figure 3 1: This figure shows that at reaction temperatures from 490 °C (and above), the PET decomposition reaction is completed within 1 minute (α = 1). This temperature is therefore suitable for the rapid conversion of PET.[23]

Studies regarding PFAS elimination

Gullett, Brian (2021): EPA PFAS Innovative Treatment Team (PITT) findings on PFAS destruction technologies. EPA Tools & Resources Webinar:
https://www.epa.gov/sites/default/files/2021-02/documents/pitt_findings_toolsresources_webinar_02172021_final.pdf

EPA (2021) US Environmental Protection Agency. Potential PFAS Destruction Technology: Pyrolysis and Gasification.
https://www.epa.gov/sites/default/files/2021-01/documents/pitt_research_brief_pyrolysis_final_jan_27_2021_508.pdf



Compound Name	Dry Biosolids (ng/g)	Biochar (ng/g)
PFBA	7.03	Not Detected
3:3 FTCA	ND	Not Detected
PFPeA	5.94	Not Detected
PFBS	2.3	Not Detected
4:2 FTS	ND	Not Detected
PFHxA	33.7	Not Detected
PFPeS	ND	Not Detected
HFPO-DA	ND	Not Detected
5:3 FTCA	64.5	Not Detected
PFHpA	7.45	Not Detected
ADONA	ND	Not Detected
PFHxS	ND	Not Detected
6:2 FTS	ND	Not Detected
PFOA	89.1	Not Detected
PFHpS	ND	Not Detected
7:3 FTCA	40	Not Detected
PFNA	5.3	Not Detected
PFOSA	ND	Not Detected
PFOS	26.3	Not Detected
9Cl-PF3ONS	ND	Not Detected
PFDA	11.3	Not Detected
8:2 FTS	5.68	Not Detected
PFNS	ND	Not Detected
MeFOSAA	23.5	Not Detected
EtFOSAA	19.6	Not Detected
PFUnA	3.39	Not Detected
PFDS	ND	Not Detected
11Cl-PF3OUdS	ND	Not Detected
10:2 FTS	ND	Not Detected
PFDoA	5.85	Not Detected
MeFOSA	ND	Not Detected
PFTrDA	ND	Not Detected
PFTeDA	2.44	Not Detected
EtFOSA	ND	Not Detected
PFHxDA	ND	Not Detected
PFODA	ND	Not Detected
MeFOSE	17.1	Not Detected
EtFOSE	ND	Not Detected

The treatment (drying and carbonization) of contaminated sewage sludge was conducted with a PYREG pyrolysis unit, no reportable PFAS were found in produced biochar of the treated sewage sludge. Of the four studied innovative technologies to eliminate the PFAS problem, pyrolysis of sewage sludge was the only one achieving a TRL of 7 (operational environment).[11]

Bioforcetech and the Environmental Protection Agency in the USA have shown PFAS degradation to non-detectable levels in both biochar[24][25] flue gas and scrubber water emissions[26][27] with pyrolysis at 600 °C for 20 minutes and subsequent thermal oxidation at 850 °C at a full-scale pyrolysis plant in California, USA. For the flue gas FTIR, analysis was performed to detect 18 C1-C8 PFAS components, showing all content values below detection limit.

Sewage sludge biochar – National EU regulations status

Biochars produced from sewage sludge have been excluded from the new Fertilizing Products Regulation (EU) 2019/1009, following the scientific opinion of the EU Joint Research Centre (JRC) technical report on STRUBIAS products[2]. However, several national regulations of EU Member States and extra-EU countries authorize the agricultural use of sludge biochars.

According to the European Sustainable Phosphorus Platform's SCOPE Newsletter nr. 144, which presents an overview of related national policies, some relevant cases can be observed in different countries, such as Denmark, Czech Republic and Sweden[6]. In these countries, the developments followed two main paths: either the greenlights could be obtained by setting up a regulation that includes biochar and PyCCS, or by proving the compliance of biochar products with existing national policies.

The following examples emphasize how national regulations are currently reflecting the need for a growing biochar industry and market, together with the necessity of a circular resource management. These Member States' initiatives can lead to an adaptation of the EU policy framework. Broad policy change can be driven by the layering of new elements and the progressive revisions to existing set of institutions[28], in this case represented by new sets of policies and active sponsorships for a regulated use of biochar. Thus, ensuring a safe and standardized management of sewage sludge, whose common practice of direct use on land is of increasing concern for the scientific community, policy makers and citizens[3].

Examples in the EU:

- **Czech Republic**: Biochar produced from sewage sludge has to be approved by national and regional authorities in order to be used in agriculture and can thus apply to obtain national end-of-waste status. On October 2021 the Amendment of Annex 1, Decree 474/200, established limit values on heavy metals and PAH (20 mg/kg DM PAH_{12}). KARBO HF s.r.o. made a successful registration for sewage sludge biochar from a PYREG installation, at Trutnovw municipal wastewater treatment plant.

- **Sweden**: Sweden's policy framework doesn't include a specific process to allow biochar from sewage sludge application into agricultural soils. The fertilising products in this national context has to follow the prescriptions of such regulations: Chapter 2 of the Environmental Code (SFS 1998:908); the regulations and general guidelines of the Swedish Board of Agriculture (SJVFS 2004:62) on environmental considerations in agriculture regarding plant nutrients; the regulations of the Swedish Environmental Protection Agency (SNFS 1994:2). Subsequentially, the product has to be registered within the Swedish Chemical Agency (KEMI). Two PYREG facilities in Germany (Unkel wastewater treatment plant and Bionero) have successfully registered biochars produced from sewage sludge as fertilising products[7].

- **Denmark**: Since June 22nd, 2022, pyrolysis is recognized as hygienisation method for sewage sludge used in agriculture by the Danish Environmental Ministry, allowing the soil application of biochar produced from sewage sludge. According to the statement, the process requirements include a minimum temperature of 500°C and a residence time of 3 minutes. Waste to be used for agricultural purposes is regulated according to Ordinance No. 1001 of 27 June 2018.

[6] see „Examples in the EU" section

[7] For more information and literature please visit the Swedish Board of Agriculture website.