# SLUDGE-BASED PYROLYSIS AS INTEGRATED BIOREFINERIES

## Safe Resource Recovery & Contaminant Elimination for Europe's Circular Bioeconomy

**BIOCHAR EUROPE POSITION PAPER**

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BIOCHAR EUROPE

# Executive Summary

In this position paper, scientific evidence and commercial information are provided to support the inclusion of biochar produced from sewage sludge in the scope of the EU Fertilising Products Regulation (FPR) 2019/1009.[1] The evidence presented is intended to support the ongoing EU "Technical Study to Support the Inclusion of New Materials and Microorganisms under the Fertilising Products Regulation", which will assess the possible integration of new materials in the FPR, such as biochar produced from sewage sludge.

This request is aligned with current EU objectives on competitiveness, circular resource management and industrial deployment: the EU Bioeconomy Strategy emphasises scaling integrated biorefineries and industrial symbiosis valleys to develop lead markets for bio-based materials and de-risk first-of-a-kind investments. In this policy framing, sewage sludge pyrolysis can be understood as a process-integrated thermochemical biorefinery pathway, converting an unavoidable residual stream into a portfolio of outputs—a nutrient-rich, sanitised solid fraction (biochar) suitable for circular fertilising products or construction materials, and carbon carriers (pyrolysis gas and, where relevant, condensates/bio-oil) that can be used on site to supply process heat and enable energy-efficient sludge drying. As a result, wastewater treatment plants can evolve from disposal cost centres into resource recovery hubs, supporting phosphorus circularity, contaminant risk reduction through controlled high-temperature conversion, and locally deployable industrial symbiosis models. This positions regulated sludge pyrolysis and biochar production not as niche waste treatments but integrated biorefinery solutions consistent with key EU strategic goals.

In 2019, the JRC report "Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009)"[2] raised specific concerns regarding the possible inclusion of sewage sludge in the positive list of feedstock for CMC14 (1) "Pyrolysis and gasification Materials". This compilation of evidence addresses the key barriers identified by the JRC, to corroborate the call for sewage sludge inclusion by meeting the requirements of Article 42 (2), Regulation (EU) 2019/1009.

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**(1)** Component Material Category 14
**(2)** Article 42 of the EU Fertilising Products Regulation outlines the possibility of amending Annexes I to IV in order to align them to technical progress and scientific evidence for new fertilizers, which a) have the potential to be the subject of significant trade on the internal market, and (b) for which there is scientific evidence that they: (i) do not present a risk to human, animal or plant health, to safety or to the environment, and (ii) ensure agronomic efficiency.

With product safety being the main concern expressed by the JRC regarding sewage sludge biochar, this paper focuses on evidence of pyrolysis potential in pollutant elimination and mitigation (Chapter 2). Subsequently, the document explores other aspects such as agricultural benefits (Chapter 3), the current technology status of pyrolysis (Chapter 4)and the existing regulation framework of certain Member States (Chapter 5)

The 2025 BCE Position Paper on Sewage Sludge Biochar concludes that biochar derived from sewage sludge should be classified under the Component Material Category 14, with a thermochemical conversion process requirement that should occur under oxygen-limiting conditions at temperatures >600°C for a minimum duration >5 min. Such additional process conditions would secure the safety of biochar from sewage sludge use in agriculture as long as PAH levels are monitored and controlled.

Pyrolysis technology (see grey box p.1) for the production of biochar from sewage sludge is widely available on the commercial market. The carbonization of this category of feedstocks can ensure product safety by minimizing and eliminating organic contaminants by advanced treatment and clearly defined process parameters.

The technology holds the potential to substantially lower wastewater management expenses and transform wastewater treatment into a resource for producing a phosphorus-rich fertilising product. Currently, a large part of the sewage sludge produced is landfilled, causing an annual 4.1 Mt $CH_4$ emissions.[3] Further, the transportation of raw sludge entails logistical challenges that can be bypassed with the local production of biochar, annexing a pyrolysis plant directly to wastewater treatment facilities. Pyrolysis can transform the carbon contained in the feedstock into a highly stable form, qualifying for permanent carbon removals. [4]

# Notes of the Authors

*This position paper serves as a working document intended to present our current understanding and perspectives on sewage sludge biochar. It reflects the best available evidence and information at the time of writing. However, it is important to acknowledge that the scientific and economic landscape is constantly evolving, and new evidence, data, and insights may emerge over time. We welcome feedback, comments, and suggestions for improvement as we strive to maintain the relevance and accuracy of this document.*

*To be cited as a Biochar Europe Position Paper with contributions from academic and industry experts.*

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## Pyrolysis

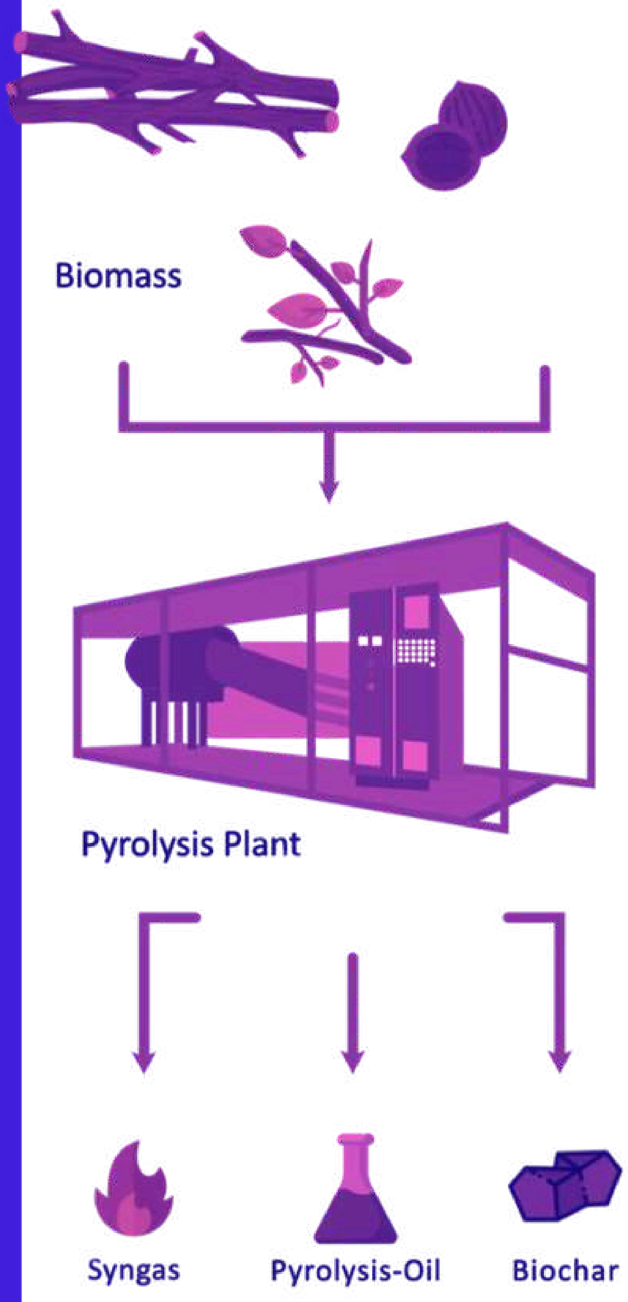
Pyrolysis is the thermo-chemical conversion of biomass in a low oxygen environment. It converts organic residues into pyrolysis gas and a stable form of carbon.

## 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.

## Biochar Carbon Removal (BCR)

While the natural degradation of organic carbon leads to the release of greenhouse gases like $CO_2$ or $CH_4$ into the atmosphere, the stable carbon fraction in biochar is extremely durable. Unless it is burned, it resists weathering/degradation and remains stable for way beyond the relevant time scales of "several centuries" [5][6][7] to thousands of years. [4]



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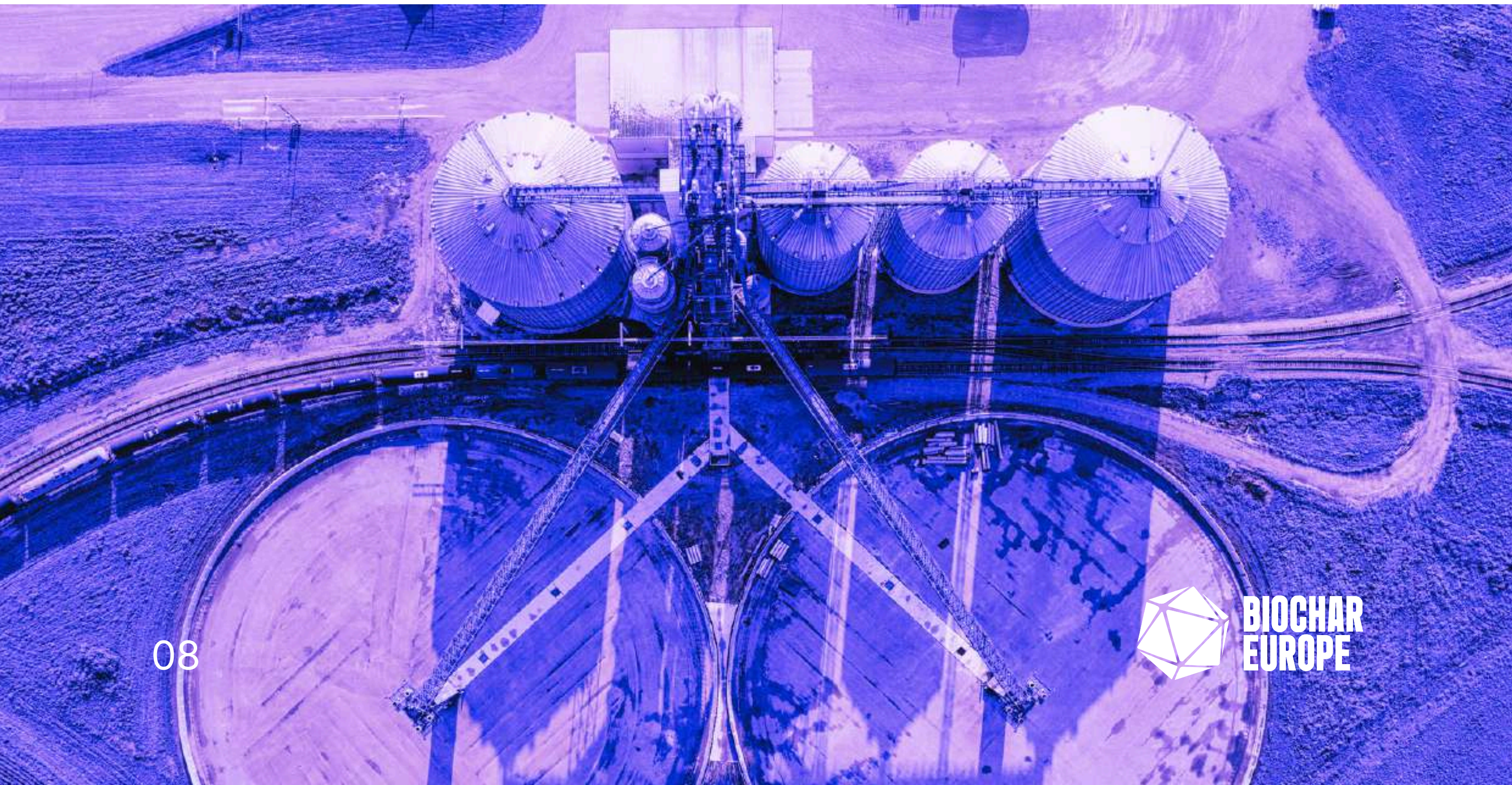
# 01

# ADDRESSING THE CONCERNS OF THE JRC GROUP ON SEWAGE SLUDGE BIOCHAR

**In the EU Fertilising Products Regulation[1] sewage sludge was excluded from the list of eligible feedstocks for "Pyrolysis and gasification materials" (CMC14). The main reasons stated by the JRC group[2] were:**

**(1.1)** Uncertainty whether contaminants of emerging concern are eliminated[3]
**(1.2)** Presumption of non-adverse effects lacks techno-scientific evidence
**(1.3)** Risk of undermining consumer confidence in biochar in general
**(1.4)** Increasing complexity of compliance scheme for the CMC group
**(1.5)** Lack of evidence on relevant benefits of biochar produced from sewage sludge
**(1.6)** Consistency with voluntary standardization schemes (EBC)

The subsequent sections of this paper delineate and address these concerns, providing chapter links to substantiate the case for biochar derived from sewage sludge incorporation in the Fertilising Product Regulation.





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### (1.1) Uncertainty whether contaminants of emerging concern are eliminated (3)

This factor stands as pivotal in the exclusion of sewage sludge from permitted CMC14 feedstock. Pyrolysis emerges as a potent method for eradicating pollutants inherent in diverse organic waste materials. Recent scientific research underscores its efficacy in tackling a wide array of contaminants typically found in sewage sludges *(refer to Chapter 2)*, spanning pathogens (2.1), pharmaceuticals (2.2.1), hormone-disrupting compounds, per- and polyfluoroalkyl substances (PFAS) (2.2.2), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs), polycyclic aromatic hydrocarbons (PAHs), organophosphate flame retardants (OPFRs) (2.2.3), and microplastics (2.3). Furthermore, residual pollutants present in biochar post-pyrolysis exhibit strong binding to its matrix, thereby mitigating risks such as heavy metal leaching into soil (2.4).

### (1.2) Insufficient techno-scientific evidence supporting the presumption of non-adverse effects

Over the past 15 years, scientific research on biochar has experienced exponential growth[8] with numerous scientific institutes and universities conducting ongoing experiments on its impact on soil and safety. This trend extends to biochar derived from sewage sludge, as evidenced by this paper's exploration of pollutant elimination through pyrolysis *(Chapter 2)* and the agricultural and environmental benefits *(Chapter 3)* it offers. Potential contaminants found in biochar may include heavy metals and organic compounds like polycyclic aromatic hydrocarbons (PAHs) and polychlorinated aromatic compounds (PCDD/Fs and PCBs).[9] However, the total content of pollutants is heavily influenced by process features and plant design, with pollutants primarily bonded to the biochar matrix, reducing soil leakage. To ensure non-adverse effects, potential pollutant content in biochar is already regulated by the Fertilising Product Regulation and specifically by CMC14 product requirements, ensuring its safe application in soil. Furthermore, implementing stricter requirements for sewage sludge pyrolysis *(Chapter 6)* would complement existing contaminant limit values.

**(3)** “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” [4]

### (1.3) Risk of undermining consumer confidence in biochar in general

Ensuring the establishment of appropriate requirements is key to safeguarding consumer trust in sewage sludge biochar. Currently, numerous Member States are authorizing its application in agriculture *(Chapter 5)*. However, permitting its use as a fertilizing product need not erode consumer confidence, provided that the Fertilising Product Regulation (FPR) delineates specific procedural standards tailored to this input material. Moreover, implementing voluntary standardization programs and certifications can bolster product credibility by transparently showcasing the processes and attributes of the biochar value chain.

### (1.4) Increasing complexity of compliance scheme for the Component Material Category 14

Firstly, it's important to note that the complexity associated with incorporating sewage sludge into the FPR need not exceed that encountered with other CMCs. By establishing uniform limit values and implementing stricter process conditions, the regulatory framework can effectively manage potential complexities. Furthermore, the FPR already addresses substances and products that may contain contaminants, suggesting that sewage sludge could be feasibly integrated into existing compliance structures. Moreover, ample scientific evidence exists to support the development of requisite requirements by policymakers. By stipulating minimum process conditions *(Chapter 6)* alongside limit values for environmental and health safety, a conformity scheme for sewage sludge as biochar feedstock can be reliably implemented. Such measures ensure both the viability of sewage sludge utilization and the preservation of environmental integrity and public health standards.

### (1.5) Lack of evidence on relevant benefits of biochar produced from sewage sludge

Indeed, the benefits arising from sewage sludge biochar are multifaceted and significant. Firstly, it offers notable agronomic advantages, enhancing soil fertility, water retention, and nutrient availability for plants (*Chapter 5* and *Annex II*). Additionally, the environmental and climate-positive impacts of sewage sludge biochar are profound, as it aids in carbon sequestration, mitigates greenhouse gas emissions, and promotes soil health and biodiversity (*Chapter 5*). Moreover, sewage sludge biochar facilitates nutrient recovery from waste materials, contributing to resource efficiency and sustainable agricultural practices, in line with the EU nutrient recovery policy. Finally, the conversion of sewage sludge into biochar presents an opportunity to transform waste into a valuable resource, potentially generating revenue streams and fostering economic sustainability. In light of these benefits, the utilization of sewage sludge biochar holds great potential for addressing agricultural, environmental, and economic challenges in a holistic and sustainable manner.

## 1.6) Consistency with voluntary standardization schemes (EBC)

The European Union's regulatory framework holds the authority to diverge from and influence voluntary certification schemes, serving as a driver of scientific advancement. As EU regulations establish robust standards grounded in scientific research and public policy considerations, they set the benchmark for safety and quality within the market. This dynamic relationship underscores the EU's role as a leading framework for guiding industry practices and innovation, particularly in areas in rapid development such as biochar and environmental sustainability.

# 02

# PYROLYSIS DESTROYS POLLUTANTS IN SEWAGE SLUDGE

**The latest scientific evidence on the elimination of the contaminants of concern in sewage sludges is presented below, including pathogens, LAS, DEHP, nonylphenols, PCBs, pharmaceuticals, PFAS, PAHs, and microplastics mitigation and elimination.**

## 2.1) Pathogens

Sewage sludge originates mainly from human excrements. Naturally, the sludge contains spores, pathogens, and pyrogens.[10] Controlled hygienization of sewage sludge may be required depending on the sludge destination and achieved through different processes with specific performance levels.

The minimum process conditions of pyrolysis are much harsher even than approved sterilization conditions. (4)

Accordingly, pyrolysis eliminates all pathogens[11] and pyrogens contained in sewage sludge – including bacteria, fungi, vira, spores, parasites, antibiotic resistance genes etc. (5)

## 2.2) Organic pollutants

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

### 2.2.1) Pharmaceuticals

(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

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**(4)** 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)**
**(5)** See "Annex I: Studies regarding contaminants elimination through pyrolysis"

Environment (Bundesumweltamt)[12] analyzed the residues of various pharmaceutical in sewage sludge 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." *(See also Annex I)*.

### 2.2.2 Per- and Polyfluoroalkyl Substances (PFAS):

PFAS are eliminated from the biochar by the process of pyrolysis. Kundu et al. (2021)[13] 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)[14] carried out on the US-based company Bioforcetech's commercially installed pyrolysis plant manufactured by PYREG shows that pyrolysis at 600°C for 10 minutes and combustion of pyrolysis gases at 850°C eliminate PFAS from sewage sludge. Bioforcetech (2021)[15] 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 600-650°C and a residence time of more than 3 minutes, with subsequent incineration of the pyrolysis gas at 850°C for more than 2 seconds, has showed to eliminate all 7 PFAS compounds, previously detected in the sewage sludge, from the biochar.[16] This experiment has been reproduced several times and showed how all PFAS detected in the sludge were eliminated (to below detection limit of target molecules) both in the biochar and in the flue gas.

G. Cornelissen et.al. performed mass balance for 56 different PFAS during full-scale pyrolysis of organic wastes, including digested sewage sludges, and demonstrated high PFAS removal (between 96.9% and 99.9% depending on the feedstock) for pyrolysis temperature of 500-800°C.[17]

Burning the pyrolysis gas destroys PFAS potentially present in the pyrolysis gas. A 2023 study carried out by US-EPA showed that the influents into the incinerator were analyzed for PFAS and compared to emissions (gaseous, liquid and solids) PFAS content to determine the PFAS destruction. Along with measuring the PFAS in the gas phase emissions with Other Test Method (OTM)-45, the emissions were also characterized for fluorinated products of incomplete destructions (PIDs) using OTM-50 and Method 0010/8270. To help evaluate the performance of the HWI, C2F6 was injected and measured using Fourier transform infrared spectroscopy (FTIR) and OTM-50. It was found that most of the PFAS that were a a high enough concentration in the influent to effectively calculate were better than 99.999% destroyed. Along with the high destruction, no PIDs were observed. This indicates that most (over 99%) of the compounds were completely destroyed, or mineralized.[18]

Recently, Moško and Gerber, co-authors of this paper, studied the effect of pyrolysis temperature and residence time on the properties of sludge biochar, including organic pollutants such as PAHs, PCBs, and 53 different PFASs. The pyrolysis was performed in a screw type reactor PYREKA at target temperatures 500, 600, and 700 °C and residence times 5, 10, and 15 minutes.

The study[19], yet in plan to be published, revealed that when pyrolysing for 5 minutes at minimum 600°C, and 10 and 15 minutes at minimum 500°C, the studied PFASs were below detection limit. The results from combination of 500°C and 5 minutes revealed detection of PFOS 3, thought it was below the limit of quantification, other studied compounds were below the detection limit.

### 2.2.3 Polychlorinated biphenyls (PCB), polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs), polycyclic aromatic hydrocarbons (PAH), organophosphate flame retardants (OPFRs), endocrine-disrupting chemicals

In the event of a concentration of PAHs exceeding the regulatory thresholds for agricultural use of sludge, additional treatment may be recommended if agronomic recovery is considered. 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)[20] demonstrated that slow pyrolysis at > 600°C removed 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"***.

Sørmo *et.al.* tested six organic wastes, including digested sewage sludges and shown that removal efficiencies for PCBs and PCDD/Fs were > 99.9% in the biochars produced in pyrolysis temperature range from 500 to 800°C.[21]

Castro et.al compared raw-, digested-, combusted and pyrolyzed sludge samples collected from different waste treatment plants. It was confirmed that pyrolysis at temperatures >500°C effectively removed the OPFRs in the produced biochar, whereas combustion at 300°C reduced the concentrations of OPFRs by 98 % (in the ashes formed).[22]

The study[19] also confirmed that none of studied PAHs and PCBs can be detected in the biochar when pyrolysing at minimum of 500°C and 5 minutes.

## 2.3 Microplastics

Depending on the destination of the sludge, elimination of microplastics might be necessary[23]. Ni et al. (2020)[24] 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). 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".*[25] PET, a highly relevant plastic type regarding sewage sludge, starts to decompose at a temperature above 450 °C and transitions to the gas phase.(6)

PET decomposition is terminated in less than one minute (α = 1) at temperatures above 500°C [26]. The cracked gases are of high calorific value and can be used for energy production. **Thus, the pyrolysis of sewage sludge is an effective method to drastically reduce microplastic in the environment.**

## 2.4 Heavy Metals Bioavailability

Sørmo et al. (2023)[27] investigated for the first time the fate of heavy metals (HM) during full-scale industrial pyrolysis (500 – 800°C) of seven contaminated feedstocks and a clean wood feedstock. Most of the heavy metals accumulated in the biochar, but As, Cd, Pb and Zn were also found in the flue gas at temperatures above 600°C. Leaching tests demonstrated that heavy metals are in fact more mobile in wood than sludge biochars. The authors explain that increased immobilization of heavy metals in sewage sludge biochar is linked to the formation of insoluble mineral species, that occurs to a larger extent in sewage-sludge-based biochars due to higher concentrations of inorganic compounds compared to wood-based feedstocks. This immobilization effect makes sewage-sludge biochars resistant towards leaching of heavy metals across a wide pH range, and to such a degree that their potential contribution of HMs to soils upon application might not necessarily be greater than that for biochars made from clean wood.

The heavy metals in the sewage sludge biochar are easily quantified. Zn, Cu, Ni, Cr, Pb typically have a concentration that is 1.6-2.0 times higher than in the sewage sludge. However, being P recovered during the pyrolysis, the ratio HMs/P remains constant.

**(6)** See Figure 3 in the Annex under "Studies regarding contaminants elimination".

Further, heavy metals leakage into soil from sewage sludge biochar is consistently lower compared to sludge direct spreading.

"It was observed that, in general, pyrolysis resulted in a statistically significant decrease in the concentrations of DTPA-extractable Cd, Cu, Pb, and Zn, as compared to their corresponding feedstock biosolids"[28]. The extractable concentrations were between 2-9 times lower than from the corresponding sewage sludge. In the table below, biochar at low temperature (BCL) has been pyrolysed at 500 °C and biochar at high temperature (BCH) has been pyrolysed at 700 °C.

| DTPA-Extractable Metals | BS | BCL | BCH |
|---|---|---|---|
| **Cd** | 0.491 ± 0.153 a | 0.056 ± 0.028 b | 0.080 ± 0.048 b |
| **Cu** | 128 ± 76 a | 45 ± 12 b | 42 ± 9 b |
| **Pb** | 1.44 ± 0.63 a | 0.72 ± 0.28 b | 0.51 ± 0.14 b |
| **Zn** | 231 ± 81 a | 26 ± 9 b | 37 ± 15 b |

***Figure 2:*** *DTPA-extractable concentrations (mg/kg) of Cd, Cu, Pb, and Zn in the biosolids and corresponding biochar samples. BS: biosolids, BCL: biochars prepared at low temperature, BCH: biochars prepared at high temperature. Different letters within the same row represent significant differences in the mean values REF _Ref163654060 \r \h * MERGEFORMAT* [28].

The mass balance of sewage sludge pyrolysis to biochar is easy to understand and predict from the sludge analysis to ensure compliance with the heavy metal limit values in the fertilizer product, which of course must be secured by further measurements as with other fertilizer products.

# 03

# BIOCHAR FROM SEWAGE SLUDGE BENEFITS FOR AGRICULTURE

**Biochar offers a sustainable method for soil management, which has the potential to enhance agricultural productivity and resilience over the long term. Biochar from sewage sludge allows to recover nutrients from a critical waste stream, promoting valuable resources management. Several studies** **(see also Annex II)** **showed different benefits for soil quality, environment and climate aspects, including emissions reduction, enhanced microbial activity, and increased biomass production, varying with the characteristics of the product and pedoclimatic conditions.**

## 3.1) Biochar contribution to carbon sinks and GHG emission reduction

Pyrolysis of sewage sludge can make a significant contribution to mitigating climate change. Containing approximately 35% of stable carbon, the biochar resulting from the process acts as a permanent carbon sink when used in agriculture. **Between 300 and 500 kg CO2 could be stored for each ton of dried sludge.**

Furthermore, storing and spreading sewage sludge directly on farmland significantly contributes to greenhouse gas (CH4 and N2O) emissions [29]. 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 1.000-1.500 kg of CO2-eq per ton of dried sludge[26] with respect to 6 months of storage of sewage sludge and direct field application and considering 100 years CO2e.

## 3.2) Biochar from sewage sludge as P-rich fertilising product

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 700 °C is the most carbon-efficient. Pyrolysis leads to a product that can be used as a P-rich fertilizing product without further chemical extraction[31]. P-recovery rates during pyrolysis can range around 80-100% of the feedstock total P content[32]. The availability of P2O5 in the biochar from sludges ranges depending on different sludges and processes and can reach 80 %, extracted with ammonium citrate [33]. According to Kratz and Schnug (2009) [34], this indicates a highly valuable fertilizing product. Sewage sludge biochar with limited water extractability on the other hand can prevent the risk of water body eutrophication due to phosphorus leakage, exacerbated by conventional mined phosphorus fertilizers use.

Additionally, the Cd/P ratio in sewage sludge biochar is typically in the range of 10-40 mg Cd/kg P dry matter, whereas this ratio can be up to 10 times higher in conventional mined phosphorus fertilizers. After the embargo against Russia, the EU needs to supply phosphorus fertilizers demand from other countries such as Morocco and Saudi Arabia, which often have Cd/P2O5 concentrations up to 1500 mg Cd/kg P2O5[35]. P-recovery from existing and undervalued sources like sewage sludge thus becomes a viable option to extract available nutrients from local sources.

Scientific publications show that with increasing pyrolysis temperature, **the plant availability of the phosphorus content gradually decreases with higher temperatures. There is an optimum >550°C - <650°C** at which the degradation of contaminants is optimal, and the agronomic effect is largely maintained.[36],[37] Therefore, BCEI recommends pyrolysis in the range of 600 – 650 °C.

## 3.3 Sewage Sludge pyrolysis yields a carbon negative P-fertilising product

In 2019, the German Federal Environmental Agency published a comparative study of phosphate fertilizers in Germany, including conventional products and respective recycled phosphates[38]. According to the publication, the current consumption of non-renewable resources for phosphate fertilising products results in emissions of around 1,2 kg CO2 eq/kg P2O5. The study emphasizes the high importance of valorizing recycled sewage sludge products to promote a more sustainable nutrient management in agriculture. In this scenario, pyrolysis of sewage sludge has a high potential to mitigate the environmental impact and global warming caused by fertilizers[39]. A calculation performed by PYREG supports this assumption: biochar from sewage sludge can obtain a Global Warming Potential (GWP) of -4,0 kg CO2 eq/ kg P2O5 (*Figure 2*). On a more general level, the urgency of addressing climate change is growing and removing carbon from the atmosphere is becoming a key solution for a sustainable future[40], in addition to emission reductions. Sequestering carbon in a durable way is thus crucial to guarantee lasting Carbon Dioxide Removal (CDR) solutions.

Biochar Carbon Removal (BCR) stands out due to its stable form of carbon and it is listed among the novel CDR methods in „The State of Carbon Dioxide Removal“ report. BCR is also now part of the permanent carbon removals defined in the soon-released EU Carbon Removal Certification Framework (CRCF). This EU legislation integrates carbon dioxide removals into its climate strategy, focusing on mature activities that offer sustainability co-benefits. In fact, BCR represents an exemplary candidate for the CRCF methodology development, due to its maturity, scalability, and efficacy in permanent carbon sequestration. Supporting the importance of biochar as a CDR solution, Sanei et al. (2024)[41] recently presented compelling evidence validating the notion of BCR as a lasting CDR solution.

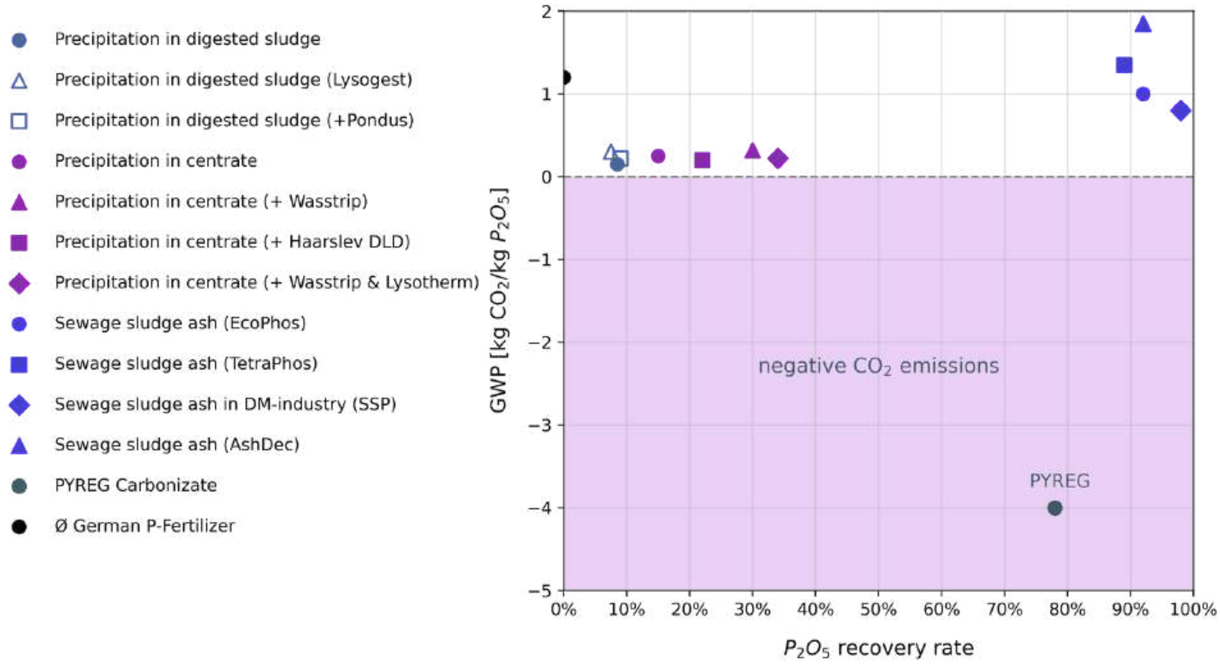


***Figure 3:*** *Diagram on Pyreg’s calculation: GWP and P recovery rates comparing common fertilizers, other P-recovery solutions and Pyreg’s biochar.*
***Source:*** *Umweltbundesamt 13/2019, S. 159; Own calculations for PYREG carbonisate.*

# 04

# PYROLYSIS TECHNOLOGY IS DEPLOYABLE AND SCALABLE

Sewage sludge pyrolysis is already a mature technology with several suppliers who have reached TRL 8 (demonstration plant) or 9 (industrial plant). For instance, some industrial plants are currently in continuous operation in Germany Czech Republic, Finland and Denmark, while demonstration plants have been operated successfully in Sweden, Germany, Italy, Australia and USA. Most of those plants work in the range of 0.5 tonne/h to 2 tonne/h of dewatered sludge (per process line), equivalent to a plant serving 50,000 PE to 200,000 PE. Therefore, they are compatible with a decentralized model, where the sludge pyrolysis plant 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 drying machine and a heat recovery system that transfers heat from the pyrolysis to the drying step. In most cases, the combination of drying and pyrolysis is energy self-sufficient with the energy recovered from the pyrolysis gas being sufficient to dry the sludge.

Digested sludge can be pyrolyzed with a fraction of green waste to reach the same result. This process would also increase the carbon content of biochar.

# 05

# 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[42], which presents an overview of related national policies, some relevant cases can be observed in different countries, such as Denmark, Czech Republic and Sweden (See below). 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[43], in this case represented by new sets of policies and active sponsorships for a regulated use of biochar.

## Examples in the EU

**Czech Republic:**
Biochar produced from sewage sludge has to obtain End-of-Waste status approved by regional authorities in order to be used in agriculture. To obtain the End-of-Waste status, the operator has to apply to regional authority, providing operating rules and certificate of the product safety and functionality (issued by Central Institute for Supervising and Testing in Agriculture), and the biochar has to fulfill limit values on heavy metals and and PAH (20 mg/kg DM PAH12) according to Decree No. 474/2000 Coll.

On the specification of requirements for fertilisers[44], which was amended with pyrolysis materials on October 2021 (Decree of the Ministry of Agriculture on setting requirements for fertilisers). KARBO HF s.r.o. made a successful registration for sewage sludge biochar from a PYREG installation, at Trutnov-Bohuslavice municipal wastewater treatment plant. After obtaining the occupancy permit for operation of the plant, the steps followed by decision of the Central Institute for supervising and Testing in Agriculture to register the product (sludge biochar) as soil improver according to Decree No. 474/2000 Coll., followed by consents and statements of the Regional Hygiene Station, the Ministry of Industry and Trade, Regional Veterinary Administration, the town of Trutnov. As a result, the Regional Office released approval to remove the sludge biochar from the waste catalogue, meaning obtaining the end-of-waste status. The fertilizing product was successfully registered as Karbofert T1.

**Sweden:**

Sweden's policy framework doesn't include a specific process to allow biochar from sewage sludge application into agricultural soils. The fertilizing 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 fertilizing products.(7)

The Swedish Revaq standard v. 9 from 01-01-2024 has also approved use of sewage sludge biochar on farmland, as long as the PAH-16 level is < 4mg/kg dm and the sewage sludge have been approved for use on farmland.

**Denmark:**

Since June 22nd, 2022, pyrolysis has been recognized as a hygienisation method for sewage sludge used in agriculture by the Danish Environmental Protection Agency, allowing the soil application of biochar produced from sewage sludge. According to the statement, the pyrolysis 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.

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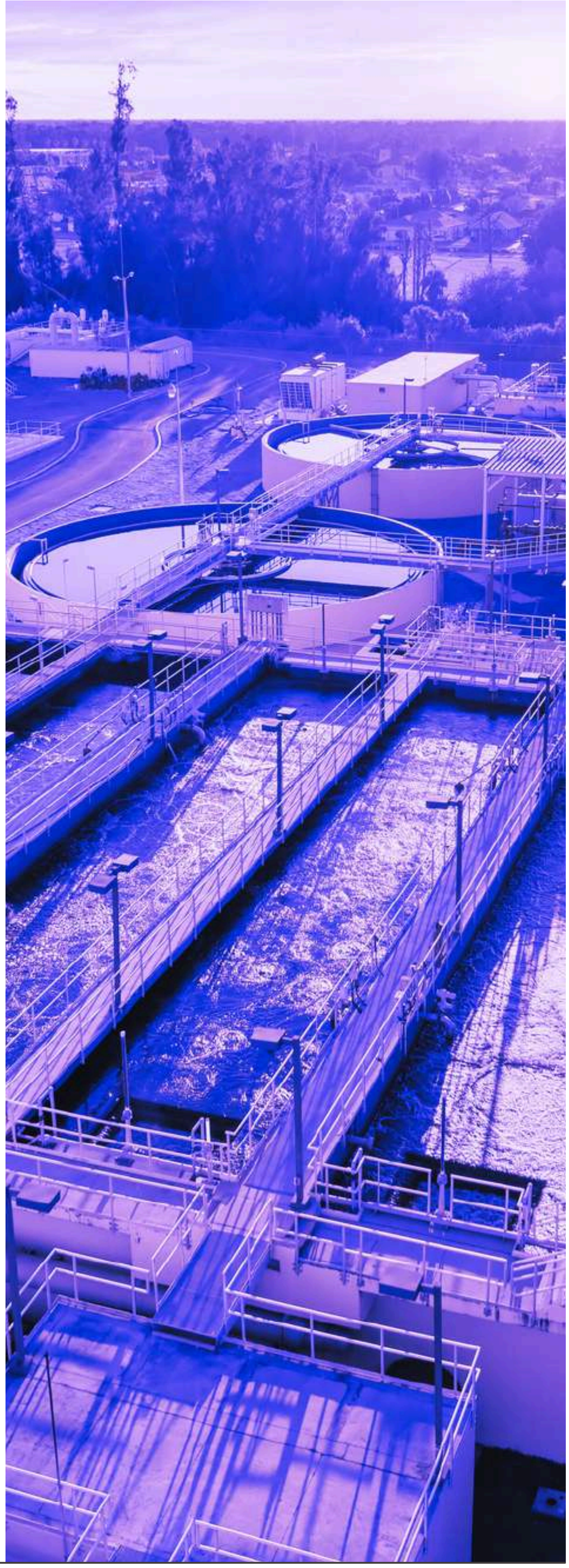
**(7)** For more information and literature please visit the Swedish Board of Agriculture website.

**Finland:**

On October 10, 2023, the Ministry of Agriculture and Forestry of Finland issued Decree 964/2023(8) on Fertilizer Products, which governs the quality requirements for product categories, input material classes, and their processing specifications for the national market. In accordance with the regulation, a fertilizer product can encompass materials produced through pyrolysis or gasification, obtained via thermochemical conversion with restricted oxygen levels. The permitted feedstocks are listed by the Food Agency, and sewage sludge is now included among them. The pyrolysis process requirements defined in the decree specify that "In the presence of plant biomass, the reactor temperature must reach at least 180 degrees Celsius for a minimum of two seconds. When utilizing sewage sludge, the reactor temperature should be raised to at least 500 Celsius degrees for a duration of at least five minutes." Additionally, a molar ratio of hydrogen (H) to organic carbon (H/Corg) of less than 0,7 and related testing are required for biochar, in addition to specific limit values for PAHs content (6 mg/kg dry matter of PAH16), in alignment with the EU Fertilising Product Regulation.



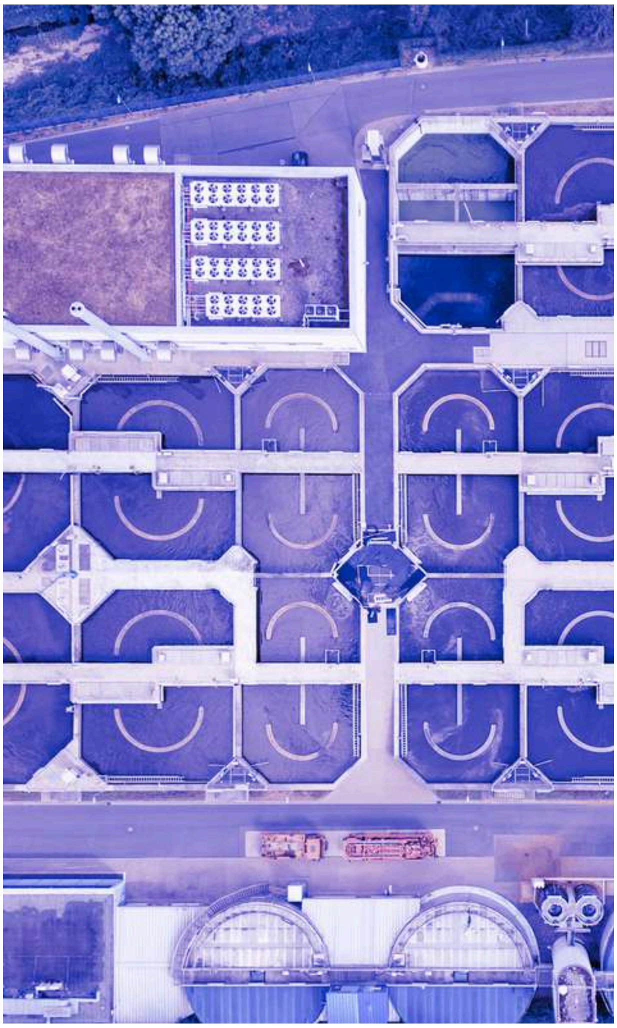
(8) Maa- ja metsätalousministeriön asetus... 964/2023 - Säädökset alkuperäisinä - FINLEX ®

# 06

# PROPOSED PROCESSING CONDITIONS FOR CMC 14

The current definition of CMC14, "Pyrolysis and gasification materials," outlined in the Fertilising Product Regulation, does not sufficiently ensure the safe production of biochar from sewage sludge. The minimum process requirements of 180°C for 3 minutes lack the necessary stringency to effectively manage hazardous pollutants of this waste stream. In light of available scientific evidence, it is recommended that biochar derived from sewage sludge is classified under CMC14, accompanied by additional process requirements. Specifically, the thermochemical conversion process should occur under oxygen-limiting conditions at temperatures > 600°C for a minimum duration >10min that ensures the full carbonization of the feedstock. Such temperature range can remove > 97% of PFAS contained in the feedstock. These minimum process standards will be supplemented with existing limit values for pollutants in the final product (CMC14) and the resulting PFC, ensuring the secure manufacturing and utilization of biochar from sewage sludge within agricultural practices.

Advanced characterization of the biochar, such as the random reflectance (Ro) analysis, can show the level of carbonization of biochar and represents an additional safety layer, also indicating pollutant degradation.



# 07

# FULFILLMENT OF ARTICLE 42 CRITERIA

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. The new fertilising products and/or components must have the potential to be the subject of significant trade on the internal market, and have scientific evidence that they do not present a risk to human, animal or plant health, to safety or to the environment, and ensure agronomic efficiency[1].

Each EU citizen generates ca. 55 g primary sludge dry solids per day or 20 kg per year[45] and approximately 8.1 million tonnes of sewage sludge are produced annually in the EU-27 (Eurostat 2021). That amounts to 2.5 Mt of organic carbon per year and 0.15 Mt of phosphorus per year[3]. Although nutrient recovery is widely encouraged in the EU, the pathways to retrieve phosphorus from sewage sludge might present different barriers. Firstly, the economic viability of sewage sludge treatment via mono-incineration, followed by the sale of recovered resources and energy at market rates, is questionable due to insufficient profitability[3] and relevant climate footprint.

The potential pyrolysis of all sewage sludge in EU would generate approximately 4 million tonnes of biochar, with recovered P (See Chapter 3.2) and C. This would constitute around 4.5 million tonnes of CO2eq sequestered per year. The CDR function of biochar can generate an additional income of 120€/tonnes CO2 eq as carbon credits (Carbonfuture.earth), other than the market value of sewage sludge biochar as a fertilizing product. Moreover, due to the sewage sludge disposal fees, pyrolysis and gasification plants that treat sewage sludge can achieve a return on investment within 5-10 years.

Sludge management costs represent up to 50 % of the operating expenses of wastewater treatment[46], with disposal costs of dewatered sewage sludge, exceeding 200 €/tonnes in certain countries [47]. There is already a substantial exchange of sewage sludge within the domestic market, and a comparable market for trading biosolids



BIOCHAR EUROPE

biochar could emerge if the obstacles to its utilization are alleviated.

The safety of sewage sludge biochar to humans and the environment can be ensured by the existing limit values for pollutants content included in the Fertilising Product Regulation and by the pollutant elimination ability of the pyrolysis process, as shown in Chapter 2 of this paper. Additionally, sewage sludge biochar is reported to be an excellent PFAS sorbent (Krahn K (2023)A), also compared to wood-based biochar.

Lastly, the agronomic efficiency of biochar has been already successfully assessed by the 2019 JRC Technical proposals for selected new fertilising materials[2]. This is complemented by the scientific literature presented in Chapter 3 and Annex II, supporting sewage sludge biochar benefits for agriculture as a fertilising product, alone or mixed with other components. Article 42 requirements are hence met.

# 08

# CONCLUSIONS

In summary, our paper advocates for the recognition and regulatory acceptance of sewage sludge biochar as a viable and beneficial resource within the EU Fertilising Products Regulation. The scientific evidence reviewed in this paper directly addressed the concerns raised by the Joint Research Centre regarding the safety of sewage sludge biochar, while presenting the agricultural, environmental and climate benefits. The multifaceted advantages cover soil health to mitigating greenhouse gas emissions and storing carbon permanently. A safe and sustainable integration of sewage sludge as allowed feedstock for CMC14 is thus possible through the implementation of stringent thermochemical conversion process requirements. Such integration would support the deployment of several EU SDGs like 13. Climate Action, 15. Life on Land, 9. Industry, Innovation and Infrastructure, 12. Responsible Consumption and Production, 6. Clean Water and Sanitation.

Through collaborative efforts between science, industry, and policymakers, we can unlock its full potential to foster sustainable agriculture together with climate benefits.

# 09

# ANNEX I - ADDITIONAL STUDIES REGARDING CONTAMINANTS ELIMINATION THROUGH PYROLYSIS

## 9.1 Studies regarding organic pollutants

**(Hoffman *et al.*, 2016)**[48] 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)**[49] 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)**[12] 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.

**(Dai et al., 2018)**[50] 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)**[51] 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)**[31] showed that pyrolysis can remove more than 95% 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.[52]

**(Simon et. al., 2018)**[53] 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 $ha^{-1}$.

**(Alipour et al., 2022)**[9] studied removal of three groups of organic contaminants - PCBs, PAHs and personal care products - showing that the removal efficiency of the compounds increased to more than 99 % in biochar at 600 °C during the pyrolysis process.

A review paper on "*Biochar from biosolids pyrolysis*" was published by **(Paz-Ferreiro *et al.*, 2018)**[11]. 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 NH4 and NO3 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)**[52]. 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.

## 9.2 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

**(Sørmo *et al.*, 2023)**[17] studied decomposition and emission factors of a wide range of PFAS during full-scale pyrolysis of wastes, including 4 sewage sludges. Concentrations of PFASs in the biochar samples were 1–3 orders of magnitude less than the concentrations in the original feedstocks, achieving removal efficiency higher than 96 % when pyrolyzed at 500 °C and higher than 98 % when pyrolyzed at 700 °C and higher. Authors state "Considering the results from the present and previous studies, pyrolysis of contaminated organic waste should be operated at a minimum of 600 °C in order to properly decompose PFAS and other organic contaminants to non-detectable levels."

In the study **(McNamara et al., 2023)**[54] pyrolysis removed more than 99 % of targeted PFAS and PFAS precursor compounds from the solid phase during pyrolysis of biosolids at 500, 650 and 800 °C. 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).[15]

Bioforcetech and the **Environmental Protection Agency (EPA) in the USA** have shown PFAS degradation to non-detectable levels in both biochar[55][14] flue gas and scrubber water emissions[56] 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.

**Bamdad, H.; Papari, S.; Moreside, E.; Berruti, F.**[57] High-Temperature Pyrolysis for Elimination of Per- and Polyfluoroalkyl Substances (PFAS) from Biosolids. Processes 2022, 10, 2187. https://doi.org/10.3390/pr10112187 **Citation:***"Biosolid samples were pyrolyzed at two different temperatures, 500 and 700 °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."*

**Jannis Grafmüller, Dilani Rathnayake, Nikolas Hagemann, Thomas D. Bucheli, Hans-Peter Schmidt,**[58]
Biochars from chlorine-rich feedstock are low in polychlorinated dioxins, furans and biphenyls, Journal of Analytical and Applied Pyrolysis, Volume 183, **2024**, 106764, ISSN 0165-2370,
https://doi.org/10.1016/j.jaap.2024.106764.
**Citation:***"As contents of PCDD/F and PCB fell below the threshold of the EBC by a minimum of factor 1.5 for PCDD/F and by 90 for PCB, despite the high Cl contents in the investigated feedstocks, there is strong evidence that pyrolysis processes with well-suited process control, i.e., limited oxygen input to the reactor, ensuring a sufficient separation of solids and gases at the biochar outlet, are not prone to produce biochars with PCDD/F and PCB contents of concern."*

**Hušek, M., Semerád, J., Skoblia, S. et al.**[59]
Removal of per- and polyfluoroalkyl substances and organic fluorine from sewage sludge and sea sand by pyrolysis.
Biochar 6, 31 **2024.**
https://doi.org/10.1007/s42773-024-00322-5
**Citation:** *"Based on our analyses, we determined that a temperature greater than 400 °C is imperative for effective PFASs and organic fluorine removal. The results were verified by analyzing samples from a commercial sludge pyrolysis unit at the Bohuslavice-Trutnov WWTP, which confirmed our measurements. In light of these results, it becomes evident that sludge pyrolysis below 400 °C is unsuitable for PFAS removal from sewage sludge."*

**Arturo A. Keller, Weiwei Li, Yuki Floyd, James Bae, Kayla Marie Clemens, Eleanor Thomas, Ziwei Han, Adeyemi S. Adeleye,**[60]
Elimination of microplastics, PFAS, and PPCPs from biosolids via pyrolysis to produce biochar: Feasibility and techno-economic analysis,
Science of The Total Environment, Volume 947, 2024, 174773, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2024.174773.
**Citation:** *"Pyrolysis eliminates >99 % of PFAS microplastics and PPCPs from biosolids. Pyrolysis can generate revenue for wastewater treatment plant."*

**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,**[61]
Can pyrolysis and composting of sewage sludge reduce the release of traditional and emerging pollutants in agricultural soils? Insights from field and laboratory investigations,
Chemosphere, Volume 364, **2024**, 143289, ISSN 0045-6535,
https://doi.org/10.1016/j.chemosphere.2024.143289
**Citation:** *"The study provides suggestive evidence that composting or pyrolysis of sewage sludges could serve as a viable strategy to preserve the advantageous effects of sludge application on soils while concurrently mitigating the hazards posed by entrained contaminants."*

**Felizitas Schlederer, Edgar Martín-Hernández, Céline Vaneeckhaute,**[62]
Ensuring safety standards in sewage sludge-derived biochar: Impact of pyrolysis process temperature and carrier gas on micropollutant removal,
Journal of Environmental Management, Volume 352, **2024**, 119964,
ISSN 0301-4797,
https://doi.org/10.1016/j.jenvman.2023.119964.
**Citation:** *"The The results revealed that through a pyrolysis temperature of ±650 ∘C and a N2 supply of 0.4 L/min during the pyrolysis and cooling processes, the concentration of organic pollutants can be reduced below their detection limit in biochar out of sewage sludge. As a result, the biochar obtained met the recommended limit values provided by EBC AgroOrganic (Version 10.3E) and IBI for all the elements studied, except for copper and zinc."*

# ANNEX II - ADDITIONAL STUDIES REGARDING AGRONOMIC BENEFITS

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)**[63] 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**)[64] 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)**[65] found **significantly increased biomass production** of Indian mustard over three years after sewage sludge char amendment to tropical soil.

**(Grutzmacher *et al*., 2018)**[66] found that amendment with sewage sludge char **reduced fertilizer induced N2O emissions by 87%** in a microcosm experiment.

**(Bai et al, 2022)**[67] also demonstrate significant yield increase for sludge based biochar (ca. 50 %, n=14), and biochar co-applied with organic and inorganic fertilizers gives the highest yield increases.

# 10

# 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;
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. Egle, L., Marschinski, R., Jones, A., Yunta Mezquita, F., Schillaci, C. and Huygens, D., Feasibility study in support of future policy developments of the Sewage Sludge Directive (86/278/EEC), Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/305263, JRC134591.
4. Hamed Sanei et. al.: Assessing biochar's permanence: An inertinite benchmark,International Journal of Coal Geology,Volume 281,2024,104409,ISSN 0166-5162, https://doi.org/10.1016/j.coal.2023.104409
5. Calvo Buendia, E., Tanabe, K., Kranj, 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. Abdeljaoued, E., Brulé, M., Tayibi, S. et al. Bibliometric analysis of the evolution of biochar research trends and scientific production. Clean Techn Environ Policy 22, 1967–1997 (2020). https://doi.org/10.1007/s10098-020-01969-x
9. Alipour, M., Asadi, H., Chen, C., Besalatpour, A.A. (2022). Fate of organic pollutants in sewage sludge during thermal treatments: Elimination of PCBs, PAHs, and PPCPs. Fuel, 319, 123864. https://doi.org/10.1016/j.fuel.2022.123864
10. 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.
11. 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

12. 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)
13. 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
14. Gullet, B., EPA PFAS innovative treatment team (PITT) findings on PFAS destruction technologies, EPA Tools & Resources Webinar February 17, 2021
15. https://ccag.ca.gov/wp-content/uploads/2020/02/BFT_FEB_2020-1.pdf
16. Sampling 28-06-2022, Eurofins Miljø og Vand A/S analytical reports AR-22-CA-22073400-01, AR-22-CA-22073409-01
17. Sormo, E., Castro, G., Hubert, M., Licul-Kucera, V., Quintanilla, M., Asimakoupolos, A. G., Cornelissen, G., Arp, H. P. H., The decomposition and emission factors of a wide range of PFAS in diverse, contaminated organic waste fractions undergoing dry pyrolysis, Journal of Hazardous Materials 454, 2023, 131447
18. Troxler, W., W. Anderson, C. McBride, J. Whitehead, M. Klingerman, J. Kumm, P. Challa Sasi, S. Yankay, M. Modiri, S. Corum, C. Adkins, E. Redman, C. Laush, S. Hall, A. Jensen, S. Waters, D. Spangler, S. Neal, T. Bales, M. Mills, P. Potter, E. Shields, W. Roberson, AND S. Jackson. PFAS Destruction by a Hazardous Waste Incinerator: Testing Results. U.S. EPA Office of Research and Development, Washington, DC, 2025.
19. Jaroslav Moško, Helmut Gerber, et al.: PFAS removal in biosolids biochar in a screw reactor as a function of residence time and temperature, unpublished results. Information on results available in person/online meeting: moskoja@vscht.cz.
20. 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.
21. Erlend Sørmo et.al. Distribution of PAHs, PCBs, and PCDD/Fs in products from full-scale relevant pyrolysis of diverse contaminated organic waste. J Hazardous Material, 2024 5:461:132546. doi: 10.1016/j.jhazmat.2023.132546
22. Gabriela Castro et.al. Analysis, occurrence and removal efficiencies of organophosphate flame retardants (OPFRs) in sludge undergoing anaerobic digestion followed by diverse thermal treatments. Sci Total Environ . 2023 20:870:161856. doi: 10.1016/j.scitotenv.2023.161856.
23. 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.
24. 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.
25. 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
26. 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.

27. Sørmo, E., Dublet-Adli, G., Menlah, G., Øyre Flatabø, G., Zivanovic, V., Carlsson, P., Almås, Å., Cornelissen, G., „Fate of Heavy Metals in Industrially Relevant Pyrolysis of Diverse Contaminated Organic Wastes: Phase Partitioning and Ph-Dependent Leaching", SSRN, 2023, http://dx.doi.org/10.2139/ssrn.4581337
28. Yumeng Yang, Barry Meehan, Kalpit Shah, Aravind Surapaneni, Jeff Hughes, Leon Fouché, and Jorge Paz-Ferreiro , Physicochemical Properties of Biochars Produced from Biosolids in Victoria, Australia, Int J Environ Res Public Health. 2018 Jul; 15(7): 1459. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6068983/
29. 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
30. 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.
31. 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
32. Chen, G., Wang, J., Yu, F., Wang, X., Xiao, H., Yan, B., Cui, X., A review on the production of P-enriched hydro/bio-char from solid waste: Transformation of P and applications of hydro/bio-char, Chemosphere, Volume 301, 2022, 134646, ISSN 0045-6535, https://doi.org/10.1016/j.chemosphere.2022.134646
33. 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?
34. 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
35. McLaughlin MJ, Tiller KG, Naidu R, Stevens DP (1996) Review: The behaviour and environmental impact of contaminants in fertilizers. Aust J Soil Res 34: 1-54
36. Buss W, Wurzer C, Bach M, Heberling J, Appel T, Gerber H, Mašek O. Highly efficient phosphorus recovery from sludge and manure biochars using potassium acetate pre-treatment. J Environ Manage. 2022 Jul 15;314:115035. doi: 10.1016/j.jenvman.2022.115035. Epub 2022 Apr 15. PMID: 35436706.
37. Thomas, Appel & Kevin, Friedrich. (2017). Phosphor-Recycling mit Karbonisaten aus Klärschlamm - Abschlussbericht Projekt 03FH088PX2. https://www.researchgate.net/publication/313024946_Phosphor-Recycling_mit_Karbonisaten_aus_Klarschlamm_-_Abschlussbericht_Projekt_03FH088PX2
38. 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.
39. 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

40. Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, J.Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A.A., Tignor, M., Vuuren, D.V., Wei, Y-M., Winkler, H., Zhai, P., Zommers, Z., Synthesis Report of the IPCC Sixth Assessment Report (AR6), Longer Report, SFs Compiled Version, (2023), https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf
41. Sanei, H., Rudra, A., Przyswitt, Z. M. M., Kousted, S., Sindlev, M. B., Zheng, X., Nielsen, S. B., Petersen, H. I., "Assessing biochar's permanence: An inertinite benchmark", Internal Journal of Coal Geology 281 (2024) 104409, https://doi.org/10.1016/j.coal.2023.104409
42. European Sustainable Phosphorus Platform, 2022, ESPP Scope Newsletter special issue on Biochars: Perspectives for pyrolysis of sewage sludges, Scope Newsletters https://www.phosphorusplatform.eu/images/scope/ScopeNewsletter144.pdf
43. Cerna, L. (2014). The Nature of Policy Change and Implementation: A Review of Different Theoretical Approaches, Semantic Scholar, Corpus ID: 16297938
44. Vyhláška č. 474/2000 Sb. Vyhláška Ministerstva zemědělství o stanovení požadavků na hnojiva (Decree No. 474/2000 Coll. On the specification of requirements for fertilisers) https://www.zakonyprolidi.cz/cs/2000-474
45. Tchobanoglous G., Burton F.L., Stensel H.D. (2003) Wastewater Engineering: Treatment and Reuse. Inc. Metcalf & Eddy, McGraw-Hill, 4th edition.
46. Poblete, I.B.S.; Araujo, O.D.Q.F.; de Medeiros, J.L. Sewage-Water Treatment and Sewage-Sludge Management with Power Production as Bioenergy with Carbon Capture System: A Review. Processes 2022, 10, 788.
47. Jakobsson, C. (2012). Sustainable agriculture (No. 1). Baltic University Press.
48. 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
49. 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
50. 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
51. 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.
52. 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
53. 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
54. Mcnamara, P., Samuel, M.S., Sathyamoorthy, S., Moss, L., Valtierra, D., Lopez, H.C., Nigro, N., Somerville, S., Liu, Z. (2023). Pyrolysis transports, and transforms, PFAS from biosolids to py-liquid. Environmental Science: Water Research & Technology, 9, 386-395. https://doi.org/10.1039/D2EW00677D
55. US EPA Research brief January 2021, Potential PFAS destruction technology: Pyrolysis and gasification.

56. 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
57. Bamdad, H.; Papari, S.; Moreside, E.; Berruti, F. High-Temperature Pyrolysis for Elimination of Per- and Polyfluoroalkyl Substances (PFAS) from Biosolids. Processes 2022, 10, 2187.https://doi.org/10.3390/pr10112187
58. Jannis Grafmüller, Dilani Rathnayake, Nikolas Hagemann, Thomas D. Bucheli, Hans-Peter Schmidt, Biochars from chlorine-rich feedstock are low in polychlorinated dioxins, furans and biphenyls, Journal of Analytical and Applied Pyrolysis, Volume 183, 2024, 106764, ISSN 0165-2370, https://doi.org/10.1016/j.jaap.2024.106764.
59. Hušek, M., Semerád, J., Skoblia, S. et al. Removal of per- and polyfluoroalkyl substances and organic fluorine from sewage sludge and sea sand by pyrolysis.Biochar 6, 31/2024 https://doi.org/10.1007/s42773-024-00322-5
60. Arturo A. Keller, Weiwei Li, Yuki Floyd, James Bae, Kayla Marie Clemens, Eleanor Thomas, Ziwei Han, Adeyemi S. Adeleye,Elimination of microplastics, PFAS, and PPCPs from biosolids via pyrolysis to produce biochar: Feasibility and techno-economic analysis. Science of The Total Environment, Volume 947, 2024, 174773, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2024.174773.
61. 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, Can pyrolysis and composting of sewage sludge reduce the release of traditional and emerging pollutants in agricultural soils? Insights from field and laboratory investigations, Chemosphere, Volume 364, 2024, 143289, ISSN 0045-6535, https://doi.org/10.1016/j.chemosphere.2024.143289
62. Felizitas Schlederer, Edgar Martín-Hernández, Céline Vaneeckhaute, Ensuring safety standards in sewage sludge-derived biochar: Impact of pyrolysis process temperature and carrier gas on micropollutant removal, Journal of Environmental Management, Volume 352, 2024, 119964, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2023.119964.
63. 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
64. 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.
65. 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
66. 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 $N_2O$ emissions in soil amended with biochar. Science of The Total Environment, 625, 1459–1466. https://doi.org/10.1016/J.SCITOTENV.2017.12.196
67. Hosseini Bai, S., Omidvar, N., Gallart, M., Kämper, W., Tahmasbian, I., Farrar, M. B., Singh, K., Zhou, G., Muquadass, B., Xu, C-Y., Koech, R., Li, Y., Nguyen, T. T. N., Zwieten, L., Combined effects of biochar and fertilizer applications on yield: A review and meta-analysis, Science of the Total Environment 808 (2022) 152073

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