Biomass Conversion and Biorefinery (2025) 15:18083–18095
https://doi.org/10.1007/s13399-025-06528-2

ORIGINAL ARTICLE

Transforming contaminated biosolids into biochar for a sustainable cement replacement material

Ravinder Kumar[1] · Anna Whelan[1,2] · Patrick Cannon[3] · Louise Reeves[4] · Elsa Antunes[1]

Received: 22 September 2024 / Revised: 9 December 2024 / Accepted: 13 January 2025 / Published online: 27 January 2025

Abstract

Contaminated biosolids especially with per- and polyfluoroalkyl substances (PFAS) in biosolids pose significant environmental risks, restricting their potential applications and necessitating sustainable solutions to address these challenges. In this context, pyrolysis emerges as a promising technology capable of degrading contaminants while transforming biosolids into useful products like biochar. This study demonstrates the application of pyrolysis at different temperatures of 450–750 °C to investigate its effect on contaminant removal and the properties of the resulting biochars. Subsequently, the biochars were utilized to prepare cement mortars by replacing 0.5, 1, 2, 4, and 6% of cement weight with biochar, and their compressive strengths were determined after 7 days of curing. The findings revealed that biosolids contained significant levels of PFAS, including perfluorooctanesulfonic acid (PFOS), 324 ng/g, perfluorohexanesulfonic acid (PFHxS), 9.15 ng/g, and heavy metals. Pyrolysis at 450 °C effectively degraded most contaminants, including PFAS. The biochar produced at 450 °C exhibited the highest concentrations of inorganic nutrients such as potassium (K), calcium (Ca), nitrogen (N), and phosphorus (P), though their levels decreased with increasing pyrolysis temperature. On the other hand, compressive strength tests for cement mortars with varying proportions of biochar replacement demonstrated that a 0.5% replacement was beneficial for all biochars (except 650 °C—biochar that achieved the maximum compressive strength with 2%). This resulted in a 30–45% increase in compressive strength compared to plain cement mortar. However, increasing the biochar content to 6% significantly reduced compressive strength. Overall, this study highlights the potential of biochar as a sustainable solution for enhancing cement mortar strength while mitigating biosolid contamination.

Keywords Biosolids · Biochar · Cement replacement · Pyrolysis · PFAS · Heavy metals

Highlights
- Biosolids contained a high concentration of 324 ng/g of PFOS.
- Pyrolysis at 450 °C removed nearly all PFAS and PPCPs.
- Pyrolysis < 550 °C produced the biochar of suitable surface area and pore volume.
- 0.5% biochar in cement mortars achieved the highest compressive strength of 6.41 MPa.
- An increase in biochar > 2% substantially decreased compressive strength.

✉ Elsa Antunes
elsa.antunes1@jcu.edu.au

[1] College of Science & Engineering, James Cook University, Townsville, QLD 4811, Australia

[2] Wastewater Operations, Townsville City Council, Townsville, QLD 4810, Australia

[3] Mackay Regional Council, Mackay, QLD 4740, Australia

[4] Queensland Water Directorate, Brisbane, QLD 4009, Australia

Abbreviations

BET	Brunauer-Emmett-Teller
CO_2	Carbon dioxide
HM	Heavy metal
PFAS	Per- and polyfluoroalkyl substances
PFHxS	Perfluorohexanesulfonic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PFDA	Perfluorodecanoic acid
PM	Polycyclic musks
PPCP	Pharmaceuticals and personal care products
STP	Sewage treatment plant
USEPA	United States Environmental Protection Agency
XRD	X-ray diffraction
℃	Degree Celsius
θ	Theta
C	Carbon
Ca	Calcium
cm	Centimetre

F	Fluorine
g	Gramme
H	Hydrogen
h	Hour
K	Potassium
kg	Kilogramme
kV	Kilovolt
L	Litre
m	Metre
mA	Milliampere
Mg	Magnesium
mg	Milligramme
MPa	Megapascal
mm	Millimetre
min	Minute
N	Newton
N	Nitrogen
Na	Sodium
ng	Nanogram
O	Oxygen
P	Phosphorous
s	Second
S	Sulphur
t	Tons

1 Introduction

The cement industry is one of the largest industries in the world. The total market size of the cement industry was estimated at $US 363.4 billion in 2022 [1]. This market is predicted to grow 5.4% in the next 5 years to reach $US 498.23 billion by 2028 [1]. In 2021, 4.3 billion tons of cement were produced worldwide, with China contributing 55% of the total production [2]. However, in 2022, approximately 4.1 billion tons of cement production was reported [2].

The production of cement is associated with several environmental concerns. The cement industry alone contributes up to 7% of the global CO_2 emissions [3]. Approximately 0.59 t of CO_2 is emitted per ton of cement produced [3]. During 2015–2021, the direct CO_2 intensity of cement production increased by nearly 1.5% per year. However, to achieve net-zero emissions by 2050, 3% annual declines are required up to 2030 [3]. Therefore, renewable and environmentally friendly alternatives to cement are highly desirable to achieve the target of net-zero emissions.

One of the promising alternatives for cement could be biochar [4]. Biochar is generally produced from biomass and organic wastes like agricultural wastes and biosolids by heating them at high temperatures and inert operating conditions [5]. The process used to produce high-quality biochar is called pyrolysis. Pyrolysis produces biochar with certain physicochemical properties that make it a suitable candidate for cement alternatives. For instance, biochar properties such as complex porous structure, high water retention ability, low thermal conductivity, and high chemical and dimensional stability are advantageous for a cementitious matrix and make biochar a favourable additive for building materials [6]. In addition, the use of biochar is beneficial in reducing carbon emissions. Depending on the physicochemical properties of feedstocks and type of biochar application, 1 kg of biochar can have average CO_2 footprints in the range of -2.0 to -3.3 kg CO_2 eq [7].

The incorporation of biochar (produced from different feedstocks and exhibiting varying physicochemical properties) in cementitious materials has been demonstrated in several previous studies [8–10]. For instance, a study produced biochar from olive stone, wood chips and rice husks using slow pyrolysis at 500 °C [8]. The prepared biochars were applied at 0.5, 1, 2, and 4% of cement replacement weight [8]. The results showed that 1% biochar-containing cement mortars achieved the highest compressive strength compared to other counterparts. The increase in compressive strength of cement mortars was ascribed to the generation of C-S-H in biochar-cement composites. The high proportion of potassium was another factor to enhance the compressive strength [11]. It is believed that potassium exhibits a greater capacity to interact with cement particles during the hydration process. Potassium acts as an alkali activating agent and accelerates the hydration process which ultimately improves the mechanical properties of cement-biochar composites [11]. Another study by Gupta et al. [4] demonstrated the preparation of biochar from mixed wood sawdust, food waste, and rice waste feedstocks. Authors utilized the biochars to prepare cement mortars using different proportions varying from 1 to 5% of the cement weight in the mortar [4]. The results showed that mortars prepared using 1% biochar from mixed wood sawdust achieved the best mechanical properties compared to other mortars prepared using biochar from food waste or rice waste [4]. The compressive strength of cement mortars using 1% biochar from wood increased by 16% after 7 days and 20% after 28 days. The increase in compressive strength was attributed to the high water absorption and retention capacity of biochar [4]. The increase in biochar quantity consistently decreased the compressive strength of cement mortars [4]. The literature suggests that the physicochemical properties of biochar depend substantially on the feedstock type which plays a pivotal role in the selection of cement admixture [8]. In addition, approximately 1–2% of biochar results in improved mechanical properties of cement mortars, while increasing the biochar quantity negatively impacts the mechanical properties.

Biosolids are organic materials resulting from the treatment of domestic sewage in a wastewater treatment facility [12]. Transforming biosolids into biochar offers a promising solution for the sustainable production of cement

replacement materials [13]. By converting a waste product into a valuable resource, we can reduce our reliance on traditional cement materials and help mitigate the environmental impact of the construction industry [12]. In 2015, approximately 33 million tonnes of biosolids production were estimated around the world, and the total market is projected to reach US$ 2.4 Bn by 2031 [14]. While in Australia, 349,000 tonnes of biosolids were generated in 2021 [15]. Out of the total biosolids proportion, nearly 91% of biosolids are applied in agriculture, land rehabilitation, and landscaping [15]. The residual 9% is suboptimally managed, either landfilled or discharged in the ocean which can lead to adverse environmental implications [15]. Especially, the presence of per- and polyfluoroalkyl substances (PFAS) in biosolids has become an alarming concern, leading to the development of strict legislation and policies around the world [14]. PFAS have been constantly detected in biosolids worldwide. Recently, Link et al. [16] investigated PFAS contamination in 350 biosolids samples from 190 wastewater treatment plants in the USA and found that the total concentration of PFAS in the samples varied from 1 to 3200 ng/g. Authors also suggested that PFAS with sulfonic functional groups constituted 71% of the total PFAS, while 29% were PFAS with carboxylic groups [16]. More contaminants like pharmaceuticals and personal care products (PPCPs), heavy metals (HMs), and polycyclic musks (PMs) have also been reported in biosolids [17, 18].

The confirmation of concerned contaminants like PFAS in biosolids poses significant risks to the environment, human health, and agriculture due to their persistence, bioaccumulation potential, and toxicity. From biosolids, PFAS can accumulate in soil, leach into groundwater, and run off into surface water, leading to long-term contamination of ecosystems. To avoid these environmental risks, the contaminated biosolids can be transformed into a safer product biochar via the pyrolysis process, and subsequently, the produced biochar can be utilized for cement replacement. Previous studies have demonstrated the use of pyrolysis to convert various biomass into biochar for cement replacement applications [8, 19]. However, less attention has been paid to utilize biosolids (or contaminated biosolids) as the feedstock for biochar production for cement replacement applications. In this study, firstly, we aim to remove the contaminants from biosolids and generate an environmental risk-free product that is biochar. Biosolids were converted into biochar using pyrolysis technology at 450, 550, 650, and 750 °C temperatures. The second aim was to evaluate the performance of biochar for construction applications. To prove this, the generated biochars were utilized to prepare cement mortars by replacing 0.5, 1, 2, 4, and 6% of cement weight with biochar. The mechanical properties like the compressive strength of cement mortars were examined to acquire the optimum biochar concentration.

2 Materials and methods

2.1 Biosolid collection

Biosolid sample was collected from the Mount St John sewage treatment plant (STP) in Townsville, Queensland, Australia, in specific and sealed containers (glass containers for PPCPs and HMs and polypropylene containers were used for PFAS). The biosolid sample was collected from the final stage of the treatment at STP. The STP uses powered polymer, mixed with the sludge before getting fed into the centrifuges. The polymer concentration is around 0.50 mg/L. The moisture content in biosolid samples was 85%. The sample was freeze-dried in a freeze dryer for 36 h. Wet and dry biosolid samples were sent to Eurofins for analysis. The samples were sent to Eurofins in an esky (filled with ice bricks) with overnight freight service, delivering the samples within 24 h. Dry biosolids were used for pyrolysis experiments.

2.2 Pyrolysis of biosolids

Pyrolysis of biosolids was carried out at 450, 550, 650, and 750 °C temperatures to examine its effect on the removal of contaminants and biochar physicochemical properties. Pyrolysis was performed in a fixed bed horizontal furnace with a heating rate of 10/min and a holding time of 1 h. Nitrogen gas was purged consistently with a flow rate of 2 L/min to ensure inert conditions. Biochar was collected and analyzed to determine the concentration of contaminants and physicochemical properties. Biochar samples were sent to the Eurofins laboratory for contaminants quantification.

HMs in the samples were analyzed using inductively coupled plasma mass spectrometry, following methods adapted from the guidelines 6010/6020 for HMs and USEPA 7470/71 for mercury. Hexavalent chromium was determined using a discrete analyzer, employing a modified version of the American Public Health Association 3500-Cr method.

For the analysis of 30 PFAS compounds, samples were processed according to methods adapted from US EPA 537.1. The procedure involved extracting the samples with basic methanol, followed by a cleanup using weak anion exchange solid-phase extraction, and then analysis using liquid chromatography with tandem mass spectrometry. The quantitation was carried out via isotope-dilution mass spectrometry, utilizing 30 matched labelled PFAS analogues.

To quantify PMs, biosolid samples were first dried at 105 °C for at least 8 h, then ground and sieved to particles

smaller than 1 mm. Approximately 10 g of the dried sample was extracted using toluene and accelerated solvent extraction. The extract was purified using a silica/Florisil® column topped with sodium sulphate and then reduced to near dryness. Deuterated polyaromatic hydrocarbons were used as surrogate internal standards, and quantitation was performed using gas chromatography coupled with time-of-flight mass spectrometry. Since galaxolide and tonalide are isobaric and cannot be separated chromatographically, the results are reported as the combined total of both compounds.

2.3 Biochar characterization

The produced biochars were characterized for their physicochemical properties, including their particle size distribution, surface area, porosity, and chemical composition using techniques such as Brunauer-Emmett-Teller (BET) and X-ray diffraction (XRD). N_2 physisorption isotherms and the specific surface area of biochars were measured at − 196 °C using a Micromeritics TriStar 3020 apparatus. Prior to analysis, the samples were degassed under vacuum at 300 °C for 6 h. The crystalline phases of biochars were analyzed using XRD. The XRD measurements were conducted with a Rigaku Ultima IV instrument, utilizing a Cu-Kα radiation source set at 40 kV and 40 mA. The spectra were obtained by scanning the diffraction angle in the 2θ range of 5–60° with a step size of 0.05°.

2.4 Preparation of cement mortars

Cement mortars were prepared using the standard test method ASTM C109/C109M at room temperature 25 ± 2 °C. A sand-to-cement ratio of 2.75 was used to prepare the mortars, and a ratio of 0.40 was used for water and mortar mixes. The biochar produced was added to the cement at different proportions (0.5, 1, 2, 4, and 6%). A plain mortar (without biochar) was also prepared. Triplicates were prepared for all compositions and plain mortar. The mortar was poured into moulds placed on a vibrating table. The vibration was continued for 40–60 s until no air bubbles emerged from the surface of the mould. All the prepared moulds were moved to a humidifier for curing at a temperature of 25 ± 2 °C. The curing process lasted for 7 days and demolding was done before analyzing the compressive strength. For this experiment, similar instruments like a humidifier, vibrating table, weighing scale, measuring cylinders, and the same batch of cement and sand were used to minimize variability. SHIMADZU AG-IC 100 kN was used to carry out the compressive strength using a rate of 50 N/s. The results were reported as the mean of three specimens with standard deviation for each composition.

3 Results and discussion

3.1 Elements and nutrients in biosolids and biochar

Table 1 shows the elemental composition of biosolids and the biochars produced at a pyrolysis temperature of 450 to 750 °C. Biosolids showed a carbon content of 29.52% and oxygen of 27%. In contrast, the pyrolysis temperature of 450 °C reduced all elements in the biochar, but a further increase in the pyrolysis temperature had no impact on the carbon content of biochar which remains nearly 25% in all biochar. However, increasing the pyrolysis temperature from 450 to 750 °C consistently decreased other elemental components like oxygen, hydrogen, and nitrogen. Carbon generally acts as a filler material in cement mortars. Therefore, higher carbon content in biochar can be considered advantageous to enhance the mechanical properties like compressive strength of cement mortars.

Table 2 presents the concentrations of primary inorganic elements observed in biosolids and produced biochars. The results suggest that compared to biosolids, the pyrolysis process helped to concentrate the inorganic elements in biochar except nitrogen which was found to decrease with an increase in the temperature. For example, biosolids contained 29,094 mg/kg of nitrogen, while the biochars produced at 450 °C and 750 °C had 27,233 and 1125 mg/kg, respectively. Among all pyrolysis temperatures, 450 °C was found to retain the maximum amount of inorganic elements

Table 1 Elemental composition of biosolids and biochars produced at various pyrolysis temperatures (450–750 °C). The table presents the percentages of nitrogen (N), carbon (C), hydrogen (H), sulphur (S), and oxygen (O) in each sample. The results highlight the changes in elemental composition with increasing pyrolysis temperature, particularly the reduction in nitrogen, hydrogen, and oxygen content. Data are expressed as mean ± standard deviation

Sample	N%	C%	H%	S%	O%
Biosolids	4.55 ± 0.03	29.52 ± 0.27	4.53 ± 0.08	0.3 ± 0	27.01 ± 0.43
Biochar 450 °C	3.49 ± 0.06	25.64 ± 0.23	1.27 ± 0.02	0 ± 0	13.98 ± 0.29
Biochar 550 °C	3.24 ± 0.01	25.51 ± 0.08	0.85 ± 0.01	0 ± 0	12.75 ± 0.14
Biochar 650 °C	2.94 ± 0.04	25.63 ± 0.33	0.5 ± 0.01	0 ± 0	11.61 ± 0.09
Biochar 750 °C	2.66 ± 0.02	25.62 ± 0.16	0.34 ± 0.01	0 ± 0	11.01 ± 0.17

Table 2 Inorganic composition (nutrients) of biosolids and biochars produced at different pyrolysis temperatures (450–750 °C). The table lists concentrations of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), total nitrogen (Total N), and total phosphorus (Total P) in mg/kg for each sample. The data demonstrate the influence of pyrolysis temperature on nutrient retention and redistribution, particularly the significant increases in phosphorus concentration in biochars compared to biosolids

Sample	Nutrients (mg/kg)					
	Ca	Mg	Na	K	Total N	Total P
Biosolids	12,400	6720	1350	5520	29,094	27,600
Biochar 450 °C	29,200	15,100	2910	13,700	27,233	58,000
Biochar 550 °C	21,400	12,500	2560	10,400	1708	34,000
Biochar 650 °C	21,400	12,500	2670	10,300	1217	34,200
Biochar 750 °C	14,600	8510	1770	6480	1125	39,100

in biochars as their concentrations were detected maximum in 450 °C-generated biochar. The proportion of inorganic elements in biochar such as K plays a decisive role to improve the mechanical properties of cement mortars. For instance, K is well known to promote the early stages of cement hydration by accelerating the formation of calcium silicate hydrate (C-S–H) gel [20]. K ions modify the microstructure of C-S-H gel, consequently, improving the mechanical properties of cement mortars [20]. Therefore, the high content of K ions in 450 °C-generated biochar can be speculated to achieve an enhanced compressive strength of cement mortars.

3.2 Characterization of biochars

Figure 1a shows the XRD pattern of the produced biochars. The peaks observed at 2 theta of 20.8, 26.6, and 50.3 can be indexed to 101, 100, and 102 planes of crystalline quartz [21]. These peaks were detected in all biochar samples. The presence of quartz in biosolids can be ascribed to the contamination of quartz-containing soils or sediments during the wastewater treatment process. In addition, equipment and infrastructure within wastewater treatment plants may contain materials made up of quartz and subsequently may be introduced in biosolids. Silica is believed to participate in pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$) produced during the cement hydration process [22], which helps in improving the compressive strength of cement mortars.

Figure 1b shows isothermal curves, and the inserted table presents the textural properties of the prepared biochar. The results suggested that the pyrolysis temperature had a significant effect on the textural properties of biochars. Among all the temperatures, 550 °C was conducive to achieve the

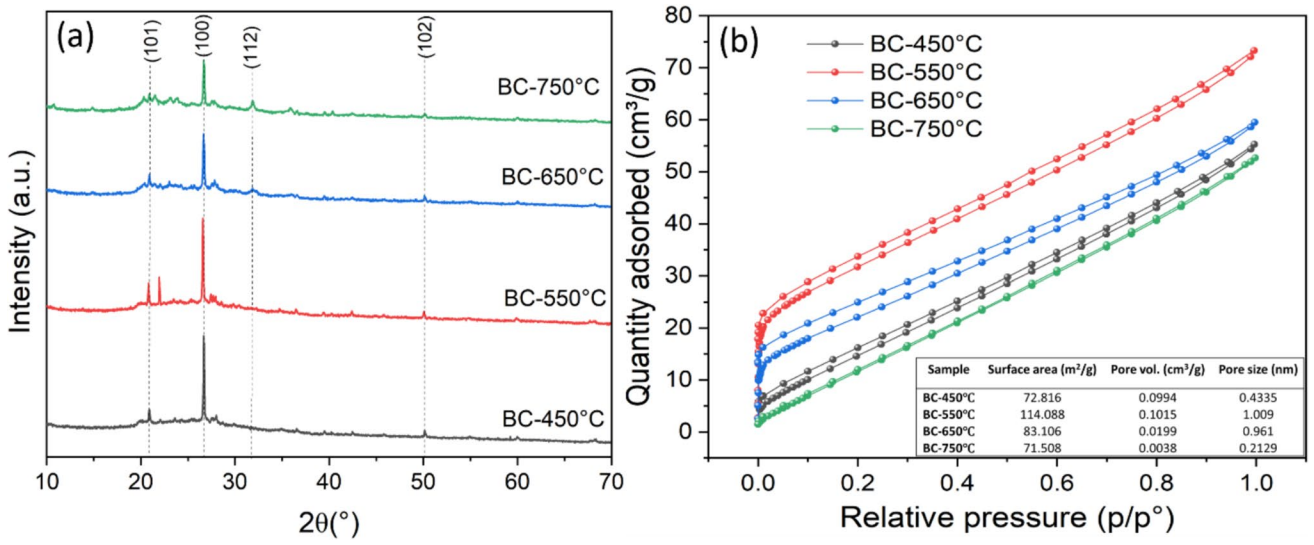

Fig. 1 **a** XRD pattern of prepared biochars at different pyrolysis temperatures. The peaks at 2 theta of 20.8, 26.6, and 50.3 can be indexed to 101, 100, and 102 planes of crystalline quartz. **b** Isothermal curves of biochars, which are Type I isotherm curves, indicating the microporous nature of the biochars. BC, biochar

biochar with better textural properties, for example, the highest surface area of 114 m^2/g and the pore volume of 0.1015 cm^3/g. On the other hand, 750 °C biochar achieved the minimum surface area and pore volume. All biochars exhibited a Type I isotherm curve, indicating the microporous nature of the biochars. The average pore size for all biochars was 1 or < 1 nm.

3.3 Contaminants in biosolids

The presence of contaminants such as HMs and PFAS in biosolids or biochar could pose significant environmental risks, and therefore, their concentrations in biochar are generally regulated for their further applications. Figure 2 shows the concentration of HMs in biosolids and biochars. For HMs, biosolids showed high concentrations of zinc (1533 ± 288 mg/kg), copper (493 ± 115 mg/kg), and manganese (263 ± 46 mg/kg). Mount St John STP receives wastewater from different catchments including industry, domestic, and agricultural activities. The high concentrations of zinc and copper can be attributed to agricultural activities like applications of pesticides and fertilizers, contamination from mining and mineral processing sites, and household wastewater containing personal care and pharmaceutical products [23]. Noticeable concentrations of boron, chromium, and lead were also observed in biosolids. Boron is naturally present in soil and groundwater, so it can be accumulated in biosolids. Industrial discharges and chemical and household products may also contain these metals which can eventually end up in the biosolids.

Figure 3a shows the concentration of selected PFAS detected in biosolids. In the PFAS category, the biosolids contained the highest concentration of 324 ± 259 ng/g of perfluorooctanesulfonic acid (PFOS), while other PFAS compounds like perfluorohexanesulfonic acid (PFHxS), perfluorooctanoic acid (PFOA), and perfluorodecanoic acid (PFDA) were present in low concentrations of < 10 ng/g. The primary sources of these PFAS compounds found in biosolids can be linked to aqueous film-forming foam-contaminated sites, wastewater originating from industries that utilize PFAS and consumer products such as non-stick cookware, stain-resistant carpets, and waterproof clothing [24]. Landfill leachate is another major source of PFAS contamination [25]. In addition, the formation of intermediate PFAS compounds during the sewage treatment process is also known [26]. The high concentration of PFOS in biosolids can also be attributed to the chemical properties of PFOS. Generally, a PFAS is made up of a dominant long-chain hydrophobic tail (with C and F atoms) and a hydrophilic head with polar chemical groups [14]. The length of the hydrophobic tail is directly related to the sorption capacity of a PFAS compound. Moreover, the type of polar groups on the hydrophilic head is responsible for the strength of electrostatic interactions with chemical groups of biosolids [27]. Sulfonated-PFAS are known to exhibit higher hydrophobicity compared to other classes of PFAS. Therefore, the high hydrophobic nature of PFOS could be one of the possible reasons for its high concentration in biosolids. However, the physicochemical properties of biosolids like pH and the presence of charged chemical species may impact electrostatic interactions with PFAS compounds and thus can influence their final concentration in biosolids [28].

Figure 3b shows the concentration of selected PPCPs observed in biosolids. The results suggest that out of 27 studied PPCPs, concentrations of only 4 compounds were found in noticeable amounts. For example, antidepressants like sertraline (1205 ± 471 ng/g) and fluoxetine (111 ± 41 ng/g), antibiotics like ciprofloxacin (120 ± 28 ng/g), and triclosan (245 ± 7 ng/g) that is an endocrine-disrupting chemical were present in biosolids. The major sources of PPCPs in

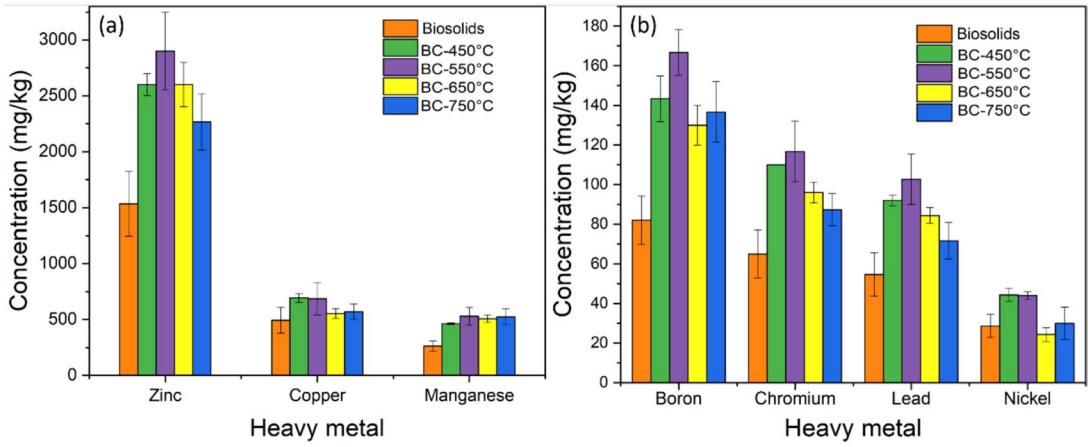

Fig. 2 Heavy metals in biosolids and the effect of pyrolysis temperature on their concentrations in biochar. Zinc was found with maximum concentration in biosolids, while its concentration was enhanced in all biochars. Error bars represent standard deviations. BC, biochar

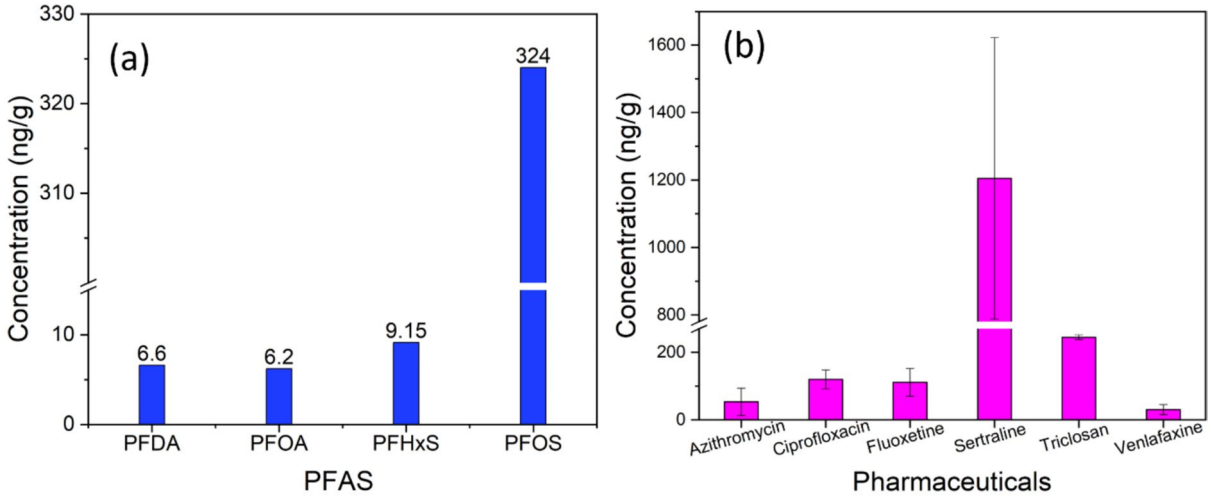

Fig. 3 **a** PFAS and **b** primary pharmaceutical products detected in biosolids. PFOS was the primary PFAS compound found in biosolids with the highest concentration. In pharmaceutical, sertraline concentration was maximum in biosolids. All PFAS and pharmaceutical compounds were successfully mitigated at all pyrolysis temperature-produced biochars. PFAS, per- and polyfluoroalkyl substances; PFDA, perfluorodecanoic acid; PFOA, perfluorooctanoic acid; PFHxS, perfluorohexane sulfonic acid; PFOS, perfluorooctane sulfonic acid

biosolids could be from wastewater generated from hospitals and other healthcare service centres, pharmaceutical industries, and domestic households.

Two PMs, galaxolide and tonalid were also examined in biosolids. A high concentration of 4171 ± 140 ng/g was detected for galaxolide, while tonalid was determined 313 ± 306 ng/g. These PMs are generally found in perfumes and deodorants, other personal care products, and detergents. Therefore, their presence in biosolids can be attributed to wastewater from household activities. Galaxolide and tonalid also exhibit low biodegradation and are possibly adsorbed on biosolids via different adsorption mechanisms like electrostatic and hydrophobic interactions [29].

3.4 Effect of pyrolysis on degradation of contaminants

Four pyrolysis temperatures of 450, 550, 650, and 750 °C were applied to investigate their effects on the mitigation of contaminants and develop a high-quality biochar that is suitable for construction applications. The results revealed that even the lower temperature of 450 °C was feasible to mitigate PFOS and other PFAS compounds since their concentrations in all biochar compounds were below the detection limit. Generally, in pyrolysis of PFOS, thermal degradation starts at the C-S bond next to the sulfonate group, which generates a nonfluorinated moiety and a perfluoroalkyl biradical C_8F_{16} [30, 31]. In the second step, defluorination of perfluoroalkyl radical occurs, followed by radical chain propagation reactions [30, 31]. Consequently, short-chain perfluoroalkyl radicals are formed which are recombined with carboxyl groups to produce perfluoroalkyl carboxylic acid intermediates [30, 31]. Finally, radical chain propagation reactions terminate to produce short-fluorinated units.

Similar to PFAS, nearly all PPCPs were degraded at all studied temperatures except caffeine which was found nearly 1 ng/g in all biochars whereas its concentration in biosolids was 11.75 ng/g. However, a high temperature of 750 °C was found best temperature to degrade PMs. On the other hand, pyrolysis temperatures (450–750 °C) showed to concentrate the majority of HMs in biochars. For example, 1533 mg/kg of zinc was present in biosolids, which increased to 2600 and 2900 mg/kg in biochar obtained at 450 and 550 °C, respectively. Similarly, manganese was found to increase from 263 mg/kg in biosolids to 530 mg/kg at 550 °C. The concentration of most HMs on a dry mass basis tends to increase in biochar compared to biosolid mainly because of the reduction in the total mass of feedstock after pyrolysis. However, the biochar obtained at the highest temperature of 750 °C showed a decrease in their concentration, suggesting the initiation of the metal volatilization process [32].

3.5 Compressive strength of biochar-amended cement mortars

Cement mortars with varying concentrations of 0.5–6% biochar prepared at different pyrolysis temperatures of 450, 550, 650, and 750 °C were developed, and their compressive strength was determined after 7 days. Triplicates of cement mortars were prepared with each concentration of all biochars, and average results with standard deviation are reported. The results of the compressive strength of cement

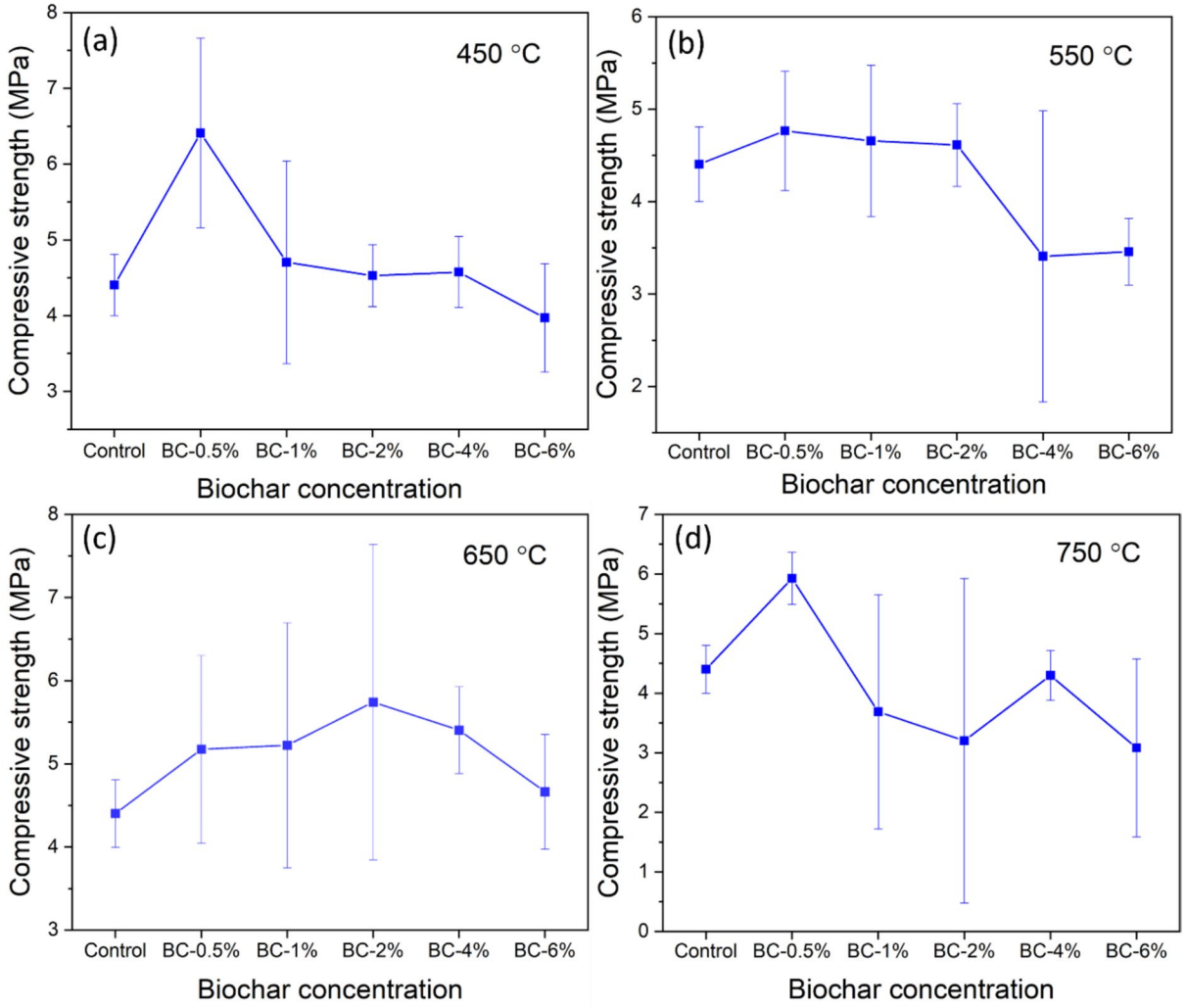

Fig. 4 Compressive strength of cement mortars prepared using varying concentrations (0.5–6%) of biochar produced at **a** 450 °C, **b** 550 °C, **c** 650 °C, and **d** 750 °C of pyrolysis temperature. Triplicates of cement mortars were prepared with each concentration of all biochars, and mean results with standard deviation are reported. A consistent trend was observed across all biochar, with the highest compressive strength at the lower biochar concentration (0.5–2%) and the lowest compressive strength at the highest concentration (6%). Error bars represent standard deviations. BC, biochar

and biochar-amended cement mortars are shown in Fig. 4. A general trend of high compressive strength with low biochar concentration (mainly 0.5%) and lowest compressive strength with 6% biochar concentration was achieved with all biochars. Interestingly, the biochars prepared at 450, 550, and 750 °C amended cement mortars showed the highest compressive strengths with 0.5% concentration, which decreased consistently with increasing biochar concentration. Notably, the highest compressive strength of 6.41 ± 1.25 MPa was achieved by 0.5% concentration of 450 °C biochar-modified cement mortar. Alternatively, the lowest compressive strength of 3.08 ± 1.49 MPa was obtained by a 6% concentration of 750 °C biochar-modified cement mortar. On the other hand, for biochar 650 °C amended cement mortars, the compressive strength increased with 0.5–2% concentration and then started decreasing with higher biochar proportions (4 and 6%). For instance, 0.5% biochar-cement mortar showed a compressive strength of 5.18 ± 1.13 MPa, which increased to 5.23 ± 1.47 MPa with 1% and further enhanced to 5.74 ± 1.90 MPa with 2%. However, increasing the biochar content to 4 and 6% decreased the compressive strength of the mortars to 5.41 ± 0.52 MPa and 4.66 ± 0.69 MPa, respectively.

Biochar improves the mechanical strength of cement mortars in several ways due to its advantageous physicochemical properties. The porous nature of biochar enhances the air content of the mortars. It acts as a micro-filler and fills the voids and gaps within the cement matrix, contributing to a denser microstructure with less overall porosity and high mechanical strength of the structure [20]. Porous biochar

may refine pore structure in the cement mortar by reducing the size and connectivity of the pores which enhances the strength and durability of the mortar. BET results indicate high pore volume for biochars obtained at 450 and 550 °C which can justify the highest compressive strength achieved by 450 °C biochar. The second most striking feature of biochar is its great capacity for water absorption [6]. Generally, the porous structure of biochar acts as a tiny water reservoir, storing water in pores and slowly releases into the matrix during the hydration process [6]. This process is also known as internal curing, where the retained water is released from the pores into the matrix and promotes the hydration process, resulting in an overall improvement of mechanical strength.

Biochar is also known to provide nucleation sites for the crystallization of hydration products due to its high surface area and porous structure [33]. Biochar composition, particularly, the presence of silica participates in pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$) produced during the cement hydration process [22]. This reaction generates two by-products; the main by-product is calcium silicate hydrate (C-S-H) and the other is calcium hydroxide. C-S-H acts as 'glue' to bind the aggregates and cement particles together to form a structural unit. The formation of C-S-H species increases the strength and durability of the mortar. In this study, XRD results indicated the presence of silica in biochars which might have undergone pozzolanic reactions with calcium hydroxide and generated C-S-H species, leading to enhance compressive strength of the mortar. Biochar enriched with potassium is also considered to enhance the hydration process and improve the strength [20]. Potassium is believed to act as an alkali-activating element and interact with cement particles through a potassium salt reaction, catalyzing the hydration process [20]. In this study, biochar obtained at 450 °C showed the highest amount of K. Therefore, the maximum compressive strength achieved by the mortar prepared using the 450 °C char can partially be attributed to K content that might have escalated the hydration process and helped in improving the compressive strength.

The compressive strength results achieved in our study were comparable to the previous studies. For instance, Onuaguluchi et al. [34] showed up to a 34% increase in compressive strength of cement mortars modified with 0.5–2% of the biochar (obtained from pyrolysis of sewage sludge). In our study, 0.5% biochar proportion (of 450 °C) in the mortar achieved a maximum increase of 45% in compressive strength compared to the plain cement mortar. Similarly, an increase of 30% and 34% in compressive strength was noticed for cement mortars with 0.5% biochar content obtained at pyrolysis temperatures of 650 and 750 °C, respectively. Another study by Gutpa et al. [4] demonstrated the application of different types of biochar in the preparation of cement mortars and showed that 1% of biochar in cement achieved the highest compressive strength while increasing the biochar content did not improve the compressive strength of the mortars. Table 3 compares more results from previous studies and provides a comprehensive comparison of compressive strength results for mortars incorporating biochars derived from various feedstocks. The table also highlights the influence of feedstock type and pyrolysis conditions on the textural properties of biochar and its impact on the compressive strength of mortars.

4 Conclusion

To conclude, it can be suggested that pyrolysis could be a sustainable technology to mitigate the environmental risks of contaminated biosolids while transforming them into an advantageous product of biochar. Pyrolysis temperature was found a decisive parameter to degrade PFAS and other contaminants, as well as biochar properties. It was found that 450 °C was effective in degrading all PFAS compounds and retaining the maximum inorganic nutrients or elements that could be of great economic value. Therefore, pyrolysis can be considered a feasible solution to mitigate contaminants in biosolids including the most concerned PFAS compounds.

In addition, the biochar produced from biosolids could be a rich source of inorganic nutrients which can be applied in agriculture, alternatively, and could also be used as a sustainable replacement for cement for construction applications. This study suggests that replacing cement with 0.5% biochar could be highly advantageous in several ways. For instance, the addition of biochar substantially increases the compressive strength of the prepared mortars; up to 45% increase in compressive strength was achieved with 0.5% biochar compared to the plain cement mortar. However, a further increase in biochar content of 4 and 6% negatively affected the compressive strength of all cement mortars.

Moreover, the production of biochar and its further application can help in reducing carbon footprints. The production of biochar through the pyrolysis process itself has shown negative net CO_2 emissions and global warming potential [20, 35]. On the other hand, the production of cement accounts for 7% of the total global CO_2 emissions. Hence, replacing cement with biochar will reduce carbon emissions. As mentioned before, 4.1 billion tons of cement production was reported in 2022 worldwide and approximately 0.59 t of CO_2 is emitted per ton of cement produced [3]. Considering the outcomes of this study and previous studies (that also showed to achieve high compressive strength with low biochar proportions) assumes that replacing 0.5% cement with biochar can avoid the production of 20.5 million tons of cement, which ultimately can help to prevent the emission of nearly 12.1 million tons of CO_2 into

Table 3 Comparison of compressive strengths of mortars incorporating pyrolysis-derived biochars from various feedstocks as partial cement replacements

Feedstock	Technique	Temperature (°C)	Biochar properties		Mortar composition (cement:sand:water)	Biochar replacement with cement (wt%)	Compressive strength (MPa) 7-days or 28 days	Reference
			BET Surface area (m^2/g)	Pore volume (cm^3/g)				
Olive stone	Pyrolysis	500	3.38	0.0021	1:3:0.5	Control	23.79	[2]
						0.5	23.53	
						1	26.36	
						2	23.60	
						4	23.00	
Forest wood chips	Pyrolysis	500	4.58	0.0077	1:3:0.5	Control	23.79	[2]
						0.5	22.61	
						1	23.96	
						2	22.71	
						4	22.71	
Rice husk	Pyrolysis	500	9.44	0.0085	1:3:0.5	Control	23.79	[2]
						0.5	22.40	
						1	24.59	
						2	23.57	
						4	24.10	
Mixed wood sawdust	Pyrolysis	500	196.92	0.071	1:2.75:0.40	Control	48.81	[3]
						1	58.08	
						2	54.09	
						5	49.25	
Food waste	Pyrolysis	500	9.70	0.0028	1:2.75:0.40	Control	48.81	[3]
						1	53.56	
						2	46.93	
						5	41.10	
Rice waste	Pyrolysis	500	35.70	0.016	1:2.75:0.40	Control	48.81	[3]
						2	45.40	
						5	43.01	
Waste wood	Pyrolysis	400	4.16	-	1:3:0.5	Control	39.15	[4]
						1	40.91	
						5	22.66	
Waste wood	Pyrolysis	500	8.89	-	1:3:0.5	Control	39.15	[4]
						1	41.29	
						5	22.78	
Waste wood	Pyrolysis	600	8.05	-	1:3:0.5	Control	39.15	[4]
						1	33.74	
						5	20.14	
Waste wood	Pyrolysis	700	7.86	-	1:3:0.5	Control	39.15	[4]
						1	32.60	
						5	16.74	
Hazelnut shells	Pyrolysis	800	-	-	0.73:0.25:0.01[a]	Control	31.76	[5]
						0.5	54.34	
						0.8	45.16	
						1	34.79	

Table 3 (continued)

Feedstock	Technique	Temperature (°C)	Biochar properties		Mortar composition (cement:sand:water)	Biochar replacement with cement (wt%)	Compressive strength (MPa) 7-days or 28 days	Reference
			BET Surface area (m^2/g)	Pore volume (cm^3/g)				
Coffee powder	Pyrolysis	800	-	-	0.73:0.25:0.01[a]	Control	31.76	[5]
						0.5	55.82	
						0.8	55.32	
						1	50.07	
Coconut shells	Pyrolysis	500	4.13	0.0065	1:2.75:0.40	Control	49.21	[6]
						5	48.62	
Commercial wood	Pyrolysis	500	372.27	0.0446	1:2.75:0.40	Control	49.21	[6]
						5	56.47	
Singapore wood	Pyrolysis	500	117.32	0.0370	1:2.75:0.40	Control	49.21	[6]
						5	51.76	
Corn stover	Pyrolysis	550	-	-	-	Control	35.41	[7]
						2	35.65	
						4	37.65	
						6	34.68	
						8	35.12	
Mixed wood sawdust	Pyrolysis	500	-	-	-	Control	150.1	[1]
						2	134.9	
						5	144.2	
						8	133.8	
Rice husk	Pyrolysis	500	9.00	0.0164	1:2:0.40	Control	68.49	[8]
						2	63.96	
						8	55.18	
Sugarcane bagasse	Pyrolysis	700	52.30	-	-	Control	35.54	[9]
						5	55.47	
						10	43.46	
Biosolids	Pyrolysis	450	72.81	0.0994	1:2.75:0.40	0.5	6.41	This study
		550	114.08	0.1015		0.5	4.76	
		650	83.10	0.0199		0.5	5.18	
		750	71.50	0.0038		0.5	5.93	

[a]Cement:water:superplasticizer

the environment. The addition of biochar also reduces the net emission of greenhouse gases and air pollutants associated with mortar mixes since biochar improves CO_2 uptake and carbonate mineralization in cement mortar [5]. Overall, the pyrolysis of contaminated biosolids to produce biochar for cement replacement presents a sustainable approach to waste recycling and also delivers substantial environmental and economic advantages.

Author contribution Ravinder Kumar contributed to experiments, data analysis, and writing the manuscript; Anna Whelan contributed to data analysis and reviewing the manuscript; Patrick Cannon and Louise Reeves contributed to editing and reviewing the manuscript; Elsa Antunes contributed to conceptualizing the idea, data analysis and editing the manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Declarations

Competing interests The authors declare no competing interests.

References

1. Expert Market Research (2024) Global cement market. https://www.expertmarketresearch.com/pressrelease/global-cement-market
2. Garside M (2023) Global cement production 1995-2022. https://www.statista.com/statistics/1087115/globalcement-production-volume
3. Mohamad N, Muthusamy K, Embong R et al (2022) Environmental impact of cement production and solutions: a review. Mater Today: Proc 48:741–746. https://doi.org/10.1016/j.matpr.2021.02.212
4. Gupta S, Kua HW, Koh HJ (2018) Application of biochar from food and wood waste as green admixture for cement mortar. Sci Total Environ 619–620:419–435. https://doi.org/10.1016/j.scitotenv.2017.11.044
5. Aman AMN, Selvarajoo A, Lau TL, Chen W-H (2022) Biochar as cement replacement to enhance concrete composite properties: a review. Energies 15:7662. https://doi.org/10.3390/en15207662
6. Liang Q, Pan D, Zhang X (2023) Construction and application of biochar-based composite phase change materials. Chem Eng J 453:139441. https://doi.org/10.1016/j.cej.2022.139441
7. Zhang Y, He M, Wang L et al (2022) Biochar as construction materials for achieving carbon neutrality. Biochar 4:59. https://doi.org/10.1007/s42773-022-00182-x
8. Maljaee H, Paiva H, Madadi R et al (2021) Effect of cement partial substitution by waste-based biochar in mortars properties. Constr Build Mater 301:124074. https://doi.org/10.1016/j.conbuildmat.2021.124074
9. Gupta S, Krishnan P, Kashani A, Kua HW (2020) Application of biochar from coconut and wood waste to reduce shrinkage and improve physical properties of silica fume-cement mortar. Constr Build Mater 262:120688. https://doi.org/10.1016/j.conbuildmat.2020.120688
10. Wang L, Chen L, Tsang DCW et al (2019) The roles of biochar as green admixture for sediment-based construction products. Cement Concr Compos 104:103348. https://doi.org/10.1016/j.cemconcomp.2019.103348
11. Restuccia L, Ferro GA (2016) Promising low cost carbon-based materials to improve strength and toughness in cement composites. Constr Build Mater 126:1034–1043. https://doi.org/10.1016/j.conbuildmat.2016.09.101
12. Elgarahy AM, Eloffy MG, Priya AK et al (2024) Biosolids management and utilizations: a review. J Clean Prod 451:141974. https://doi.org/10.1016/j.jclepro.2024.141974
13. Paz-Ferreiro J, Nieto A, Méndez A et al (2018) Biochar from biosolids pyrolysis: a review. IJERPH 15:956. https://doi.org/10.3390/ijerph15050956
14. Kumar R, Dada TK, Whelan A et al (2023) Microbial and thermal treatment techniques for degradation of PFAS in biosolids: a focus on degradation mechanisms and pathways. J Hazard Mater 452:131212. https://doi.org/10.1016/j.jhazmat.2023.131212
15. Australian Biosolids Statistics (2021) Biosolids production in Australia 2010 – 2023. https://www.biosolids.com.au/guidelines/australian-biosolids-statistics
16. Link GW, Reeves DM, Cassidy DP, Coffin ES (2024) Per- and polyfluoroalkyl substances (PFAS) in final treated solids (biosolids) from 190 Michigan wastewater treatment plants. J Hazard Mater 463:132734. https://doi.org/10.1016/j.jhazmat.2023.132734
17. Ren B, Shi X, Jin X et al (2021) Comprehensive evaluation of pharmaceuticals and personal care products (PPCPs) in urban sewers: degradation, intermediate products and environmental risk. Chem Eng J 404:127024. https://doi.org/10.1016/j.cej.2020.127024
18. Kumar R, Vuppaladadiyam A, Antunes E et al (2021) Emerging contaminants in biosolids: presence, fate and analytical techniques. Emerg Contam 8:162–194. https://www.sciencedirect.com/science/article/pii/S2405665022000117
19. Dixit A, Gupta S, Pang SD, Kua HW (2019) Waste valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete. J Clean Prod 238:117876. https://doi.org/10.1016/j.jclepro.2019.117876
20. Maljaee H, Madadi R, Paiva H et al (2021) Incorporation of biochar in cementitious materials: a roadmap of biochar selection. Constr Build Mater 283:122757. https://doi.org/10.1016/j.conbuildmat.2021.122757
21. Antunes E, Schumann J, Brodie G et al (2017) Biochar produced from biosolids using a single-mode microwave: characterisation and its potential for phosphorus removal. J Environ Manage 196:119–126. https://doi.org/10.1016/j.jenvman.2017.02.080
22. Sirico A, Bernardi P, Sciancalepore C et al (2021) Biochar from wood waste as additive for structural concrete. Constr Build Mater 303:124500. https://doi.org/10.1016/j.conbuildmat.2021.124500
23. Kumar R, Whelan A, Cannon P et al (2023) Occurrence of emerging contaminants in biosolids in northern Queensland, Australia. Environ Pollut 330:121786. https://doi.org/10.1016/j.envpol.2023.121786
24. O'Connor J, Bolan NS, Kumar M et al (2022) Distribution, transformation and remediation of poly- and per-fluoroalkyl substances (PFAS) in wastewater sources. Process Saf Environ Prot 164:91–108. https://doi.org/10.1016/j.psep.2022.06.002
25. Abunada Z, Alazaiza MYD, Bashir MJK (2020) An overview of per- and polyfluoroalkyl substances (PFAS) in the environment: source, fate, risk and regulations. Water 12:3590. https://doi.org/10.3390/w12123590
26. Zhang J, Gao L, Bergmann D et al (2023) Review of influence of critical operation conditions on by-product/intermediate formation during thermal destruction of PFAS in solid/biosolids. Sci Total Environ 854:158796. https://doi.org/10.1016/j.scitotenv.2022.158796
27. Cai W, Navarro DA, Du J et al (2022) Increasing ionic strength and valency of cations enhance sorption through hydrophobic interactions of PFAS with soil surfaces. Sci Total Environ 817:152975. https://doi.org/10.1016/j.scitotenv.2022.152975
28. Ebrahimi F, Lewis AJ, Sales CM et al (2021) Linking PFAS partitioning behavior in sewage solids to the solid characteristics, solution chemistry, and treatment processes. Chemosphere 271:129530. https://doi.org/10.1016/j.chemosphere.2020.129530
29. Clara M, Gans O, Windhofer G et al (2011) Occurrence of polycyclic musks in wastewater and receiving water bodies and fate during wastewater treatment. Chemosphere 82:1116–1123. https://doi.org/10.1016/j.chemosphere.2010.11.041
30. Xiao F, Sasi PC, Alinezhad A et al (2021) Thermal decomposition of anionic, zwitterionic, and cationic polyfluoroalkyl substances in aqueous film-forming foams. Environ Sci Technol 55:9885–9894. https://doi.org/10.1021/acs.est.1c02125
31. Alinezhad A, ChallaSasi P, Zhang P et al (2022) An investigation of thermal air degradation and pyrolysis of per- and polyfluoroalkyl substances and aqueous film-forming foams in soil. ACS EST Eng 2:198–209. https://doi.org/10.1021/acsestengg.1c00335
32. He J, Strezov V, Zhou X et al (2020) Pyrolysis of heavy metal contaminated biomass pre-treated with ferric salts: product characterisation and heavy metal deportment. Biores Technol 313:123641. https://doi.org/10.1016/j.biortech.2020.123641
33. Praneeth S, Guo R, Wang T et al (2020) Accelerated carbonation of biochar reinforced cement-fly ash composites: enhancing

and sequestering CO2 in building materials. Constr Build Mater 244:118363. https://doi.org/10.1016/j.conbuildmat.2020.118363
34. Onuaguluchi O, Mohamed B, Adwan A et al (2024) Sludge-derived biochar as an additive in cement mortar: mechanical strength and life cycle assessment (LCA). Constr Build Mater 425:135959. https://doi.org/10.1016/j.conbuildmat.2024.135959
35. Fawzy S, Osman AI, Mehta N et al (2022) Atmospheric carbon removal via industrial biochar systems: a techno-economic-environmental study. J Clean Prod 371:133660. https://doi.org/10.1016/j.jclepro.2022.133660