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Review

Challenges and Remediation Strategies for Per- and Polyfluoroalkyl Substances (PFAS) Contamination in Composting

Sali Khair Biek [1,2], Leadin S. Khudur [1,2,*] and Andrew S. Ball [1,2]

[1] ARC Training Centre for the Transformation of Australia's Biosolids Resource, RMIT University, Bundoora, VIC 3083, Australia; s3681949@student.rmit.edu.au (S.K.B.); andy.ball@rmit.edu.au (A.S.B.)
[2] School of Science, STEM College, RMIT University, Bundoora, VIC 3083, Australia
* Correspondence: leadin.khudur@rmit.edu.au

Abstract: Municipal solid waste (MSW) is projected to rise to 3.4 billion tonnes by 2050, with only 33% undergoing environmentally friendly management practices. Achieving a circular economy involves sustainable approaches, among which diverting waste from landfills to composting plays a crucial role. However, many of the products society uses and discards in MSW daily contain per- and polyfluoroalkyl substances (PFAS), raising concerns that composts may inadvertently introduce PFAS into the environment, posing a significant challenge to waste management and environmental sustainability. PFAS have been detected in compost at concentrations ranging between 1.26–11.84 μg/kg. Composts are therefore a source of PFAS contamination, posing risks to human and ecosystem health. Impactful technologies are therefore required for PFAS remediation during the composting process. This review examines the composting process as a sustainable organic waste management technology, examining the various systems employed, compost quality, and uses, particularly emphasising the challenge posed by PFAS contamination. The review provides novel insights into possible PFAS remediation technologies. A comprehensive understanding of PFAS origin, fate, and transformation during the composting process is lacking, creating substantial knowledge gaps regarding the inputs processes contributing most to PFAS accumulation in the final product. Addressing these gaps in future studies is crucial for minimising PFAS discharge into the environment and developing an effective remediation approach. This review highlights the urgent need for innovative solutions to mitigate PFAS contamination in compost and the importance of advancing research and technology to achieve sustainable waste management objectives.

Keywords: circular economy; compost; composting process; immobilisation; PFAS; waste management

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1. Introduction

With a global population of more than 8 billion (U.S. Census Bureau International Database 2023), a significant increase in global municipal solid waste (MSW) is projected, presenting a major, growing concern [1]. MSW is an assorted mixture of wastes, including components such as yard waste, kitchen waste, and various types of garbage that are discarded and collected daily [2]. It is estimated that about 2 billion tonnes (Bt) of MSW are generated annually worldwide, and this value is projected to grow to 3.4 Bt of MSW by 2050. Currently, only 33% of the overall production is treated using an environmentally safe management system [3].

The organic fraction constitutes the largest component of MSW, accounting for between 28% and 64% (*w*/*w*) basis of total MWS [4]. This fraction can be utilised as a resource for different technologies, such as composting, which represents an economically feasible way to treat and valorise the organic fraction of MSW into a valuable product [5,6].

Composting, which is defined as the natural biological decomposition of organic materials carried out by microorganisms in an aerobic environment, represents one of the most widely used approaches to the utilisation of the organic fraction of MSW [7,8]. This method of waste recycling and treatment diverts organic materials into nutrient-rich, stabilised and sanitised compost, free of pathogens and plant seeds [9,10].

The environmentally friendly agricultural supplement "compost" can be used as an organic fertiliser (biofertiliser) or soil amendment that improves soil's physical, chemical, and microbiological features, providing nutrients for plant growth, increases soil water retention, and reduces the dependence on fossil fuel-based fertilisers [11]. However, despite its numerous beneficial uses, contaminants (physical, chemical, and microbial) have been reported in compost products that may pose risks to human health and the environment. Plastic, heavy metals, and other chemical contaminants have been the subject of much research, and reduction measures have been put in place [12]. However, to date, limited scientific data have been published on the occurrence and quantification of per- and polyfluoroalkyl substances (PFAS) in composts. PFAS are synthetic organic chemicals comprising more than 12,000 compounds, as listed in the U.S. Environmental Protection Agency (EPA)'s PFAS master list, that were used as additives to a wide variety of industrial and household consumer products due to their chemical and thermal stability and hydrophobic and oleophobic properties [13,14]. Due to their persistence and recalcitrance to degradation as a result of their strong carbon–fluorine bonds, they have the potential to bioaccumulate and biomagnify in biota [15,16,17] and have toxic effects [18,19]. PFAS have been linked to different types of cancer, such as kidney and testicular cancer, altered immune and thyroid function, kidney disease, liver disease, and adverse development and reproductive outcomes [20]. Recently, the International Agency for Research on Cancer (IARC), the specialised cancer agency of the World Health Organization, reclassified PFOA as a Group 1 carcinogen, indicating it is carcinogenic to humans, and categorised PFOS as Group 2B, potentially carcinogenic to humans [21].

Composting as a waste management system reuses organic waste, but it can reintroduce persistent PFAS contaminants into the environment. The application and use of PFAS-contaminated compost will discharge PFAS or their transformation products directly and/or indirectly into the soil and then by plant uptake, and potentially transfer PFAS into the food chain, resulting in a human and ecosystem health risk [22,23,24]. By disposing of PFAS-containing products at the end of their service life, they enter the waste stream and are present in high volume, which can lead to their environmental release via a number of routes that cause contamination of water, soil, and air [25,26,27].

Composts are therefore a possible source of PFAS contamination in the environment and agricultural food pathways. Given the increasing global awareness and concern regarding the environmental and health impacts of PFAS, regulations on PFAS in compost and their usage are becoming more stringent. Some studies have been conducted on the presence of PFAS in compost; however, to the best of our knowledge, studies have yet to comprehensively investigate the occurrence and transformation of PFAS during the composting process and the potential of PFAS precursors to transform into other PFAS products. Significant gaps therefore exist in understanding which inputs and process stages contribute the most to PFAS accumulation in the final compost product.

This review aimed to comprehensively explore current knowledge of the presence and fate of PFAS during composting. The review also assesses possible remediation strategies to address the environmental and health challenges posed by PFAS in composting practices and the final product. This will assist composters and regulators in developing protocols that minimise PFAS discharges into the environment by understanding the mechanisms underlying their potential removal during composting and proposing novel solutions to be applied and mitigate the adverse impacts of compost application.

2. Sustainable Organic Waste Management-Composting

On average, globally, each person produces 0.74 kg of solid waste daily, ranging between 0.11 to 4.54 kg, resulting in the worldwide generation of 3.4 billion tonnes (Bt) of MSW by 2050 [3,3,28]. The world is expected to generate more than 11 million tonnes (Mt) per day by 2100 [29,30]. Among the total MSW generated globally, organic waste (food and green waste) is the largest category, accounting for 44% [31].

Currently, the most used global waste management methods are landfilling and open dumping due to their cost-effectiveness and low technical requirements, even though they have a higher overall environmental impact. Landfilling is the traditional waste disposal practice through burial at designated sites, whereas open dumping is dumping the waste in an open environment [32,33]. Globally, an estimated 70% of the total generated waste is either disposed of in landfills or dumped in open areas, while only 19% of the total global waste collected is taken for environment-friendly treatment methods, such as composting and recycling [34]. In terms of the environmental management of organic waste, composting stands out as a promising solution for tackling the issue of organic waste on a global scale. As the world strives to improve both environmental and human health, composting offers a cost-effective, eco-friendly, and feasible approach to recycling organic waste.

3. The Composting Process

Composting, as a means of recycling organic waste, offers numerous environmental benefits through waste reduction, resource reuse and buffering the effects of climate change. It significantly contributes to reducing greenhouse gas emissions by diverting organic waste from landfills. According to the Australian Economic Advocacy Solutions (AEAS), in Australia during 2018–2019, composting accounted for an annual reduction of approximately 3.8 Mt of CO_2-equivalent greenhouse gas emission by recycling organic waste. This is equivalent to removing 877,000 cars from the road or planting 5.7 million trees [35]. In addition, composting reduces the volume of waste entering the landfill by up to 30%, resulting in a product that can have beneficial uses [36].

Different aerobic composting methods are currently in use, including static piles, windrows, in-vessel, and vermicomposting (Table 1) [37,38].

Table 1. Description of different composting methods used.

Composting System	Description
Static pile composting	• Conventional method, Simple system. • Minimal turning or maintenance. • Piles of organic materials rely on natural processes for decomposition. • Commonly used for larger-scale outdoor composting.
Windrow composting	• Conventional method. • Piles of organic materials placed in a long narrow pile called "windrows". • Regularly turned to aerate and facilitate decomposition. • Commonly used for large-scale composting.
In-vessel composting	• Organic waste processed in closed containers or vessels such as bins, beds, tanks, or rotating drums. • Controlled decomposition by regulating temperature and moisture. • Uses forced aeration and mechanical turning. • Ideal for urban areas or space-restricted sites. • A high level of automation reduces labour and land demand, and there is less susceptibility to ambient climate conditions.
Vermicomposting	• Utilises worms to break down organic matter into nutrient-rich compost. • Commonly used for smaller-scale composting.

Each method applies specific conditions and requirements to ensure efficient and environmentally responsible organic waste management. The choice of method will be based on the volume and type of the feedstock, available space, time required for monitoring and maintenance, cost, intended use of the compost, odour control requirements, environmental goals, and regulations [39,40].

3.1. Stages of Composting

Regardless of the method used, the basic process of composting usually consists of five stages: pre-treatment, primary fermentation, secondary fermentation, post-treatment and storage, and deodorisation [40]:

- Pre-treatment: The starting materials (feedstock) undergo pre-treatment (screening, sorting, crushing, and homogenising) to achieve optimal conditions to aid microbial growth, which accelerates the composting process. Certain conditions must be met: carbon-to-nitrogen (C:N) ratio between 25–30:1, a moisture level between 45% and 65%, a neutral pH between 5.5 and 8.5, and a well-structured pile for adequate ventilation with particle sizes between 3 and 15 mm; these values may differ slightly across various references [41].
- Primary fermentation: During the initial composting phase, the pile temperature rapidly increases to >60 °C from ambient temperatures, driven by the intense activity of thermophilic bacteria. Abundant O_2 is required for breaking down organic compounds such as proteins, fats, and carbohydrates [42].
- Secondary fermentation: In this maturation stage, further decomposition by actinomycetes and fungi, which become more active at this stage, occurs, utilising organic materials unused by other microorganisms [43]. The remaining organic matter is converted into more stable humus or humus precursors within the compost pile.
- Post-treatment and storage: At this stage, the final product can undergo a range of procedures to ensure the product's high-quality standard as a commercial fertiliser. Those procedures include screening, sieving, drying, nutrient supplementation, microbe inoculation, pelleting, packaging, etc., to ensure the product meets the standards required for commercial compost.

Odour-control procedures must be included in each stage of the composting process, as odorous gases, such as ammonia (NH_3) and volatile organic compounds, are produced and continuously released, especially in the initial stages. Procedures such as feedstock pre-treatment and the use of equipment, e.g., air purification, are mandatory to minimise the diffusion of odour gases to the surrounding environment [44].

3.2. Phases of Composting

Under optimal conditions, composting proceeds through three phases: mesophilic, thermophilic, and cooling and maturation (Figure 1). The temperature profile determines the specific microorganisms that will dominate at each phase [11,45].

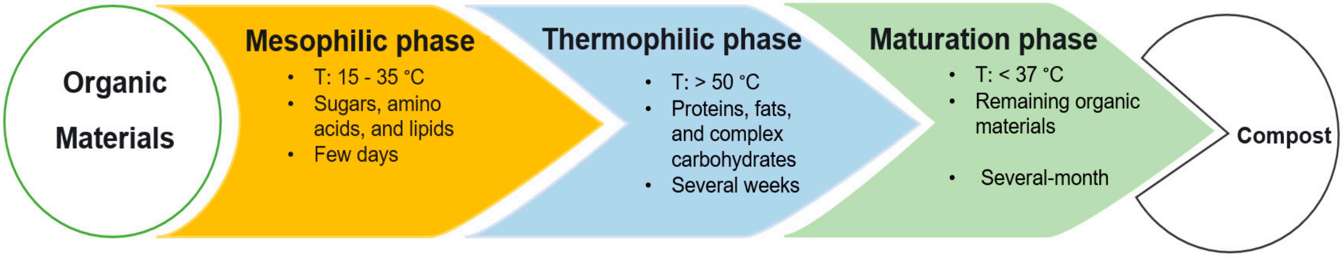

Figure 1. The phases of the composting process.

The mesophilic phase initiates decomposition at temperatures between 15 °C and 35 °C, driven by mesophilic microorganisms and fungi. These organisms utilise soluble and easily degradable raw material components such as sugars, amino acids, and lipids, leading to a rapid temperature increase. Subsequently, the thermophilic phase begins as temperatures rise above 50 °C, led by thermophilic microorganisms, including actinobacteria, which decompose proteins, fats, cellulose, hemicellulose, lignin, and plant structural molecules. This phase is essential for hygienisation as pathogens, weed seeds and insect larvae are destroyed as temperatures can reach 65–85 °C. The final phase involves cooling and maturation, with decreased microbial activity and temperature, facilitating mesophilic organisms to degrade the remaining organic matter. During the biodegradation processes, organic compounds are broken down into CO_2 and NH_3. This final phase is critical, as stabilisation and humification of the organic matter produce a mature compost with humic characteristics.

4. Compost Quality

During composting, putrescible organic matter is converted into mineralised products such as nitrogen (N), sulphur (S), phosphorus (P), and other inorganic compounds, together with stabilised organic matter, primarily in the form of humic substances (compost) [46,47].

Mature compost is a dark, crumbly, and earthy-smelling nutrient-rich substance. The physical and chemical characteristics of compost vary, depending on the nature of the feedstock, the extent of decomposition and the conditions in which the composting process operates. This product can be used for multiple purposes and deliver a variety of benefits by modifying a wide range of chemical, physical, and biological soil properties [48].

The quality of compost is evaluated based on two key indicators: “stability” and “maturity”. The stability of compost refers to the degree of organic matter decomposition, with resistance to further decomposition and potential for long-term storage, determined using indices of microbial activity. The maturity of compost refers to the extent to which the process has been completed and the degree to which organic matter has broken down and transformed into a stable humus-like substance; it is associated with plant-growth potential or phytotoxicity [49].

To ensure the safety, efficacy, and sustainable use of compost as a valuable product, numerous countries have established compost quality standards or guidelines. In Australia the “Australian Standard for Composts, Soil Conditioners and Mulches” (AS4454-2012) state the minimum requirements of compost’s physical, chemical, and biological properties to facilitate the beneficial recycling and use of compostable materials with minimal adverse effects on environmental and human health. This standard covers different aspects, including maturity, stability, acceptable content of contaminants, nutrient content, and microbial safety, as well as guidelines for labelling, and documentation to ensure that they meet established quality standards and are suitable for their intended purpose [50,51,52].

The use of good-quality compost as a soil amendment has positive effects on the biological processes in the soil and improves its physical and chemical properties, resulting in higher crop productivity and improved environmental quality. There are numerous advantages of using compost, such as increasing soil structural stability, supporting plant growth, contributing to reducing greenhouse gas emissions, and more, summarised in Table 2 [53,54,55,56].

Table 2. The benefits of compost use

Purpose of Use	Advantages
Soil Amendment:	• Improves soil structure. • Improves soil organic matter. • Enhances soil water retention. • Increases nutrient content and availability.

	• Promotes soil fertility. • Reduces soil erosion. • Balances pH levels. • Stimulates soil biological activity and microbial biomass.
Plant Growth:	• Supports healthier plant growth. • Provides essential plant macro- and micronutrients such as nitrogen (N), phosphorus (P) and potassium (K) • Controls soil-borne pathogens. • Encourages root growth and development. • Reduces reliance on synthetic fertilisers.
Erosion control:	• Helps prevent soil degradation and runoff. • Stabilises slopes and disturbed areas. • Provides a protective layer for plant roots. • Preserves topsoil integrity.
Waste management:	• Reduces the volume of waste. • Reduces the amount of waste sent to landfills. • Supports eco-friendly and sustainable waste management practices.
Carbon sequestration:	• Contributes to carbon sequestration. • Mitigates climate change.
Environmental impact:	• Minimises methane emissions from landfills. • Reduces reliance on chemical inputs. • Enhances long-term soil health and productivity.

In addition to the beneficial uses outlined in Table 2, compost has also been effectively employed to bioremediate contaminated soils with heavy metals (Zn, Cu, Ni, Cd, Pb, Cr and Hg) and organic pollutants (OPs), such as polycyclic aromatic hydrocarbons (PAHs), pesticides, petroleum, and other pollutants, providing a degrading matrix for large numbers of active microorganisms aided by available nutrients that promote degradation [57,58,59].

5. Compost Contaminants

Compost is a potential source of physical (plastic and glass), chemical (heavy metals and organic pollutants), and microbial contamination (pathogens), owing to the extremely heterogeneous nature of the waste [60,61]. The migration of these contaminants from soil to plant and ultimately to humans through the food chain can be a major limiting factor for the use of compost. There are excellent reviews in the literature covering physical and biological contaminants in compost. This review will focus on the potential chemical contamination of compost through heavy metals and organic pollutants (Table 3).

Table 3. Chemical contamination of compost

Contaminant Type	Explanation of Risk	References
Inorganic Contaminants		
Heavy metals (e.g., Cd, Co, Cr, Cu, Pb, Ni and Zn)	• A study in Switzerland showed the mean values of heavy metals for compost ($n = 81$) ($mg\ kg^{-1}$ dw) as follows: Cd→Co→Cr→Cu→Ni→Pb→Zn 0.13→4.1→20→60→16→54→155 Below the legal threshold values, which are: Cd→Co→Cr→Cu→Ni→Pb→Zn 1→ - → - →100→30→120→400 • Repeated applications of compost to soil may lead to an accumulation of heavy metals.	[62,63]

	• At high concentrations, heavy metals can cause toxicity to plants and negatively affect animal and human health and soil microbial processes. • Compost contamination by heavy metals is generally well studied and controlled in compost applications such as source-separated waste collection. • The addition of compost can reduce the bioavailability of heavy metals, reducing the risk of their migration to plant tissues by increasing soil sorption capacity and heavy metal retention.	
Organic contaminants		
Pesticides (e.g., DDT, cyprodinil, dichlobenil, aldrin, and chlordane)	• Pesticides in compost can cause damage to soil quality and plant growth. • May result in endocrine disruption and carcinogenic impacts on humans, transferring through the food chain. • A study showed the concentrations (n = 15) (µg kg d.m.$^{-1}$) of pesticides at a windrow composting plant on day 0 and after 14, 56, and 112 days of composting: Day 0 → 14 → 56 → 112 Pesticides (Sum) 43→28→10→14 • The concentration of these pesticides decreased over time during the composting process, indicating that composting can be an effective method for reducing the concentration of pesticides in organic waste.	[64]
Polychlorinated biphenyls (PCBs)	• Used in a wide range of industrial applications such as oil in transformers, plasticisers, dielectrics in capacitors, and more. • PCBs are persistent in the environment. • They bioaccumulate and transfer through the food chain. • Their human health adverse effects include cancer and endocrine disruption. • A study showed successful biodegradation of polychlorinated biphenyls (PCBs) up to approximately 16% in the composting process, depending on their chlorination level.	[65]
Polycyclic aromatic hydrocarbons (PAHs)	• PAHs can be emitted from: o Natural sources such as volcanic eruptions and natural forest fires. o Mainly originate from anthropogenic sources such as industrial manufacturing of PAHs and from the incomplete combustion of fossil fuels, wood, and tobacco. • PAHs in compost can affect soil health and plant growth. • Cause human adverse health effects, such as carcinogenicity and teratogenicity. • A study in European countries showed the concentration (µg kg^{-1} dw) of PAHs (∑12 PAHs) in compost samples (n = 88) ranged between 1.2×10^2 and 2.6×10^4 µg kg^{-1}, dry mass (dm). • Comparison with European limit values, which range from 4 to 10 mg kg^{-1} dw, the compost samples complied with the limits.	[66]
Per- and polyfluoroalkyl substances (PFAS)	• PFAS can bioaccumulate and biomagnify through the food chain. • They have potential health and environmental risks. • Recent studies revealed PFAS concentrations of Σ38 in compost (n = 4) ranging from 1.26 to 11.84 µg kg^{-1} dw, indicating widespread contamination. • The same study showed a 2- to 3-fold increase in the concentrations of PFCAs using the total oxidisable precursor assay. • This can be explained due to the occurrence of PFAS precursors in the samples that may transform into more stable and potentially toxic PFAS compounds.	[23,67]

	• PFAS are linked to several adverse health effects, such as low infant birth weights, cancer, thyroid hormone disruptions, and asthma, raising alarms about their presence and fate in compost. • Current analytical methods for PFAS detection in compost are still evolving and focus on a limited number of compounds, suggesting a potential underestimation of the full extent of PFAS contamination. • The diversity and complexity of PFAS compounds significantly hinder efforts to fully assess and mitigate their impact on compost quality and safety.

dw: dry weight.

The presence of contaminants in compost has been extensively studied and measures for reduction have been implemented; however, current knowledge is insufficient to allow the presence and management of PFAS, despite the fact that this is a contaminant of concern in this context [12]. Currently, there are no federal regulations for PFAS in compost worldwide. The standard for compost regulation in Germany includes specific limits of 0.1 mg/kg for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) combined. Similarly, Austria has implemented limits for these PFAS compounds [51]. However, soil screening levels (industrial and commercial) for different PFAS compounds have been defined in some countries, such as Canada and some states in the USA [68]. In Australia, the AS 4454-2012 standard specifies general and specific requirements for composts as previously prescribed; however, PFAS in compost are not explicitly included [23,52]. Regulations, legislation, and guidelines for managing PFAS are still being developed, and understanding of the fate of PFAS during the composting process and its potential impacts on the environment and human health is now an urgent research issue.

6. Per- and Polyfluoroalkyl Substances (PFAS)

PFAS are fluorinated organic compounds often referred to as “forever chemicals” due to their extreme persistence in the environment. The recent definition of PFAS in 2021 by the OECD (Organisation for Economic Co-operation and Development) defined PFAS as substances that have at least one fully fluorinated methyl ($-CF_3$) or methylene carbon ($-C_nF_{2n}-$) [69,70], deviating from the definition of Buck et al. of PFAS as “highly fluorinated aliphatic substances that contain one or more C atoms on which all the H substituents have been replaced by F atoms, in such a manner that they contain the perfluoroalkyl moiety ($–C_nF_{2n+1}$)” [13]. This revised definition broadens the range of fluorochemicals, and most noticeably includes many pharmaceuticals and pesticides that are now part of the PFAS family. These compounds have vastly different applications, diverse ecological footprints and different environmental impacts [71,72].

PFAS may be classified into long-chain PFAAs, including perfluoroalkyl carboxylic acids (PFCA, $C_nF_{2n+1}COOH$, $n \geq 7$), perfluoroalkane sulfonic acids (PFSA, $C_nF_{2n+1}SO_3H$, $n \geq 6$), and their potential precursors (PASF- and fluorotelomer-based compounds). Short-chain PFAS includes PFCAs where $n \leq 6$ or PFSAs where $n \leq 5$ [13]. The length of the fluorinated carbon chain strongly impacts their physicochemical properties, affecting their behaviour in composts and the environment, as well as their distribution, bioaccumulation, and toxicity [73].

The widespread use of PFAS has resulted in their presence in various environmental matrices, including composts, as well as solid wastes, wastewaters, surface waters, groundwaters, soils, and sediment [74,75,76,77]. Despite their widespread use, they were not initially detected and documented in the environment, wildlife, and humans, as PFAS testing was not broadly available until the early 2000s [78,79,80].

However, as research and scientific literature increased, awareness of the potentially harmful effects of PFAS on human health, wildlife, and the environment grew. In particular, long-chain PFAA, perfluorooctanoic acid (PFOA or C_8 PFCA), perfluorooctane sulfonic acid (PFOS or C_8 PFSA), and their precursors are recognised as global contaminants of high concern due to their persistence [81], accumulation in living organisms and biomagnification potential through the food web [82,83]. PFAS precursors such as PASF-based substances can be partially transformed biotically or abiotically into PFCAs and/or PFSAs in the environment and biota. Similarly, FT-based substances can also undergo partial transformation into PFCA [81,84,85,86].

Several PFAS are classified as persistent organic pollutants (POPs) and are listed in the Stockholm Convention. Namely, PFOS, its salts, and perfluorooctane sulfonyl fluoride (PFOSF) are listed as POPs in Annex B (Restriction) in the 2009 literature. In 2019, PFOA, its salts, and PFOA-related compounds were listed in Annex A (Elimination), resulting in global restrictions on their production and uses [87]. Recently, in 2022, perfluorohexane sulfonic acid (PFHxS), its salts, and PFHxS-related compounds were listed in Annex A to the Convention [88].

Driven by concerns about their adverse effects on humans and the environment, PFAS have received increased attention worldwide in the regulatory and scientific community. Consequently, many countries have phased out or are in the progress of phasing out their production and use [89,90,91,92]. In Australia, some PFAS have been monitored, and the use and import of some PFAS, as part of the Global Monitoring Plan (GMP) under the Stockholm Convention on POPs, have been regulated, leading to the development of regulatory, policy, and voluntary approaches to the response to PFAS contamination [93]. Following this voluntary progress, global production has shifted toward the production of PFAS precursors due to their higher degradation potential and shorter-chain homologues, which are assumed to have a lower bioaccumulation potential [94,95]. However, short-chain PFAS such as perfluorobutane sulfonic acid (PFBS) and perfluorobutanoic acid (PFBA) are more persistent, less adsorbable, and more mobile, and thus could transport to remote regions and pose lasting environmental impact [96,97].

Disposal of PFAS-containing products in MSW as a terminal repository for consumer, commercial, and industrial solid wastes will subsequently return those forever chemicals into the environment through leaching, air transport and other pathways. As they are environmentally persistent, PFAS can move through the waste cycle indefinitely [98]. Current methods of managing waste perpetuate the cycle of contamination, as PFAS are readily detected and by-products of treatment methods such as composts [23,99] and biosolids [100,101], which can then contaminate soil, water, and crops.

7. The Source of PFAS in Compost

PFAS are introduced into compost via the feedstock materials that are processed throughout the composting process, the liquids that are used in the process, or through air-borne PFAS deposited by dust on the composted material [102]. The unique chemical and physical properties of PFAS have led to their extensive use over many years in numerous industrial, commercial, and consumer applications. Products such as food service products, textiles, and paper may introduce PFAS directly into the waste stream, while pesticides and fertilisers may contribute to waste stream contamination indirectly [103]. Research by Goossen et al. found that the levels of PFAS in compost produced from manure and compostable service ware were 20 to 45 times higher than those found in compost made from separated food waste with manure and grass clippings [99]. However, to date, few studies have reported and compared the occurrence of historical PFAS in composts from different feedstock [104,105].

The presence of PFAS in food service-ware was confirmed by a study that found the average concentration of fluorotelomer alcohols (FTOHs) in eco-friendly paper tableware and popcorn bags were 2990 ng/g and 18,200 ng/g, respectively [106]. Those FTOHs can transform into other PFAS during the composting process, similar to the transformation of 6:2 FTOH into PFAS degradation products such as PFPeA, PFHxA, PFBA, 5:3 FTCA, and 4:3 FTCA during sewage sludge composting [107]. Similarly, under aerobic conditions, biodegradation of 8:2 FTOH generates long-chain PFOA as the main terminal product, in addition to PFBA, PFPeA, PFHxA, PFHpA and PFNA [108].

Limited information is available on the transformation of PFAS precursors during the composting process and also the possibility of long-chain PFAS breaking down into shorter-chain PFAS, which are more mobile in the environment and can easily contaminate groundwater and surface water. There is a pressing need for research to understand how composting affects PFAS compounds during the process.

Among their numerous applications, PFAS have been used as an active and/or inactive ingredient in biocides (pesticides and herbicides) and fertiliser formulations. Their role as an additive helps pesticide delivery by functioning as surfactants, in addition to their use as coating ingredients in fertilisers [109]. The long-chain PFOS was found with concentrations in the range of 3.92–19.2 mg/kg in 6 of 10 insecticide formulations tested, suggesting a high likelihood of uptake by crops in areas where these insecticides have been used [110].

Food waste streams may also be a source of PFAS contamination in compost: in a comparison between composts made with and without food waste, one study reported that compost containing food waste had higher PFAS levels than green waste compost [22]. PFAS contamination is widespread in food products such as seafood and livestock products (e.g., meat), possibly because of bioaccumulation. Also, crops that end up in composting feedstock will contribute to compost PFAS contamination due to uptake of PFAS from polluted soil or water [111]. Liu et al. found $\sum$PFAS ranged from 58.8 ng/g to 8085 ng/g in ten vegetables (including celery and carrots) and three grain crops (wheat, corn, and soybean) [112].

The application of compost to agricultural land to improve soil health and crop productivity may inadvertently transfer PFAS to the soil, which are then taken up by plants and crops or released in localised surface runoff or leach into groundwater [24,113,114,115]. Plant uptake of PFAS through the application of compost is an important pathway of animal and human exposure to PFAS [113]. Therefore, it is critical to identify approaches for the remediation of PFAS in compost to decrease their bioavailability in compost to protect the food supply, the environment, and human health.

Remediation of PFAS in biowaste products can be achieved by focusing on minimising the source of PFAS contamination, i.e., source control or elimination prior to soil application. Efforts to control PFAS exposure by reducing the usage of PFAS-containing products represent a beneficial approach. However, reducing PFAS exposure is challenging due to the ubiquity of PFAS in modern life and the effort required from various sectors, including policymakers and regulatory bodies [67,116].

At present, the primary focus of remediation technologies is the targeting of aqueous waste streams contaminated with PFAS. Technologies such as sorption using granular activated carbon, biochar [117,118], ion exchange resins [119], membrane technologies including reverse osmosis (RO) and nanofiltration (NF) membranes [120], advanced oxidation (i.e., chemical, electrochemical, and photochemical) [121,122], and foam fractionation [123] have been studied and/or used to treat waterbodies such as wastewater, drinking water, groundwater, and leachate [124].

In contrast, the application of PFAS remediation technologies developed for solid media is categorised into three broad approaches, namely, mobilisation (e.g., phytoremediation, soil washing, and soil flushing), immobilisation (e.g., sorption and stabilisation), and destruction (e.g., biodegradation, thermal treatment, chemo-oxidation, and ball milling) [125,126]. Most studies have focused on the treatment of PFAS-contaminated soil remain in the experimental phase, while others have been tested in the field. Among these techniques is stabilisation [127,128,129].

In addition, some of those technologies have been adapted for solid biowaste products such as biosolids, yet to the best of the authors' knowledge, no studies have been conducted on the remediation of PFAS in compost. The following section focuses on technologies for the remediation of PFAS in soil and biosolids, which are considered feasible for managing PFAS-contaminated compost. However, compost may have different considerations due to its organic nature and susceptibility to leaching, which may impact the choice and effectiveness of remediation techniques [130].

8. Potential Treatment of Per- and Polyfluoroalkyl Substances in Composts

As there is currently a lack of studies on PFAS remediation approaches in compost, this review discusses potential approaches that may be suitable for compost use. The suitability for use in compost of each remediation technology in addition to their advantages and disadvantages are listed in Table 4.

For the input stage of the composting system, the primary intervention for PFAS is source control, which can be achieved through standard measures to control known sources of PFAS contamination. Source control involves identifying the sources of PFAS reaching the organic waste used for composting and the development of guidelines to minimise these sources reaching the waste [67].

Mobilisation uses various amendments, such as surfactants and solvents, to facilitate the desorption of PFAS, making them more mobile and easier to remove, allowing for subsequent remediation [125,131,132]. The mobilised PFAS can then be treated by phytoremediation through plant uptake or by soil washing and flushing [133,134,135,136,137]. Most studies have focused on the uptake and accumulation of PFAS in different plant species from biowaste-amended soils, such as edible crops, which are not suitable for use in phytoremediation purposes [24,138,139].

In immobilisation, the amendment has the opposite effect: to immobilise PFAS in their original environment, thereby decreasing their mobility and bioavailability. A wide range of amendments has proven efficient in treating PFAS-contaminated soil and biosolids, including activated carbon (AC), biochar, modified clay minerals like bentonite and kaolinite, titanium dioxide, or a combination of different amendments to enhance the effectiveness of immobilisation [140,141,142,143,144,145,146]. Zhang and Liang assessed the potential for managing PFAS bioavailability in biosolids to timothy grass using immobilisation and mobilisation. Their findings demonstrated the efficacy of stabilising PFAS and reducing their bioavailability by adding the sorbent (i.e., granular activated carbon (GAC), RemBind, biochar) to biosolids. In contrast, treating biosolids with the surfactant (e.g., sodium dodecyl sulphate) significantly increased plant uptake, which could be a valuable approach for enhancing PFAS removal if phytoremediation is applied [147]. The mobilisation approach is potentially less ideal for composts due to risks of incomplete PFAS extraction, whereas the immobilisation approach could lead to PFAS retention in compost used for agricultural purposes, highlighting the need for both methods to undergo extensive research and development to ensure their efficacy and safety in treating PFAS during the composting process.

Destruction of PFAS in solid media can be achieved through degradation processes, using either biotic processes such as biodegradation [148,149] and/or abiotic treatment such as thermal treatment, i.e., incineration, commonly used for treating PFAS in soil [150,151], and pyrolysis of biosolids [152], advanced oxidation/reduction treatment [153,154], and mechanochemical treatment (e.g., ball milling) [155,156]. Research into biodegradation approaches is ongoing, revealing degradation pathways for specific PFAS compounds. This suggests bioremediation as a promising approach in tackling PFAS contamination, with potential for the degradation of specific PFAS species within the composting environment. Generally, destruction technologies are not suitable for use to treat PFAS in compost due to the high temperatures involved and the potential disruption to the composting process.

Selection of a remediation technology that is potentially likely to be effective for composts should be based on site-specific conditions, the specific PFAS compounds present, the level of contamination, treatment goals, and regulatory requirements, among other considerations [157]. Furthermore, selection should be based on the treatment efficacy and ability to produce a good-quality compost that functions as a safe, effective organic fertiliser.

Table 4. Advantages and disadvantages of PFAS remediation technologies applicable to composts.

Approach	Technique	Advantages	Disadvantages	Suitability for Use in Compost	Reference
Mobilisation	Phytoremediation	• Sustainability (natural process). • Cost-effective. • Requires minimal equipment. • Erosion control. • Minimal destruction of the contaminated site. • Carbon sequestration. • Biodiversity protection. • Enhances the aesthetic. value of the remediation site. • Can be applied in situ and ex situ.	• PFAS do not readily biodegrade. • Possibility of converting long-chain PFAS into stable medium-chain PFAS. • Limited plant species. • Time required, i.e., slow process. • Potential toxic effects on plants and risk of PFAS entering the food chain (bioaccumulation). • Limited practical application: affected by toxicity, climatic conditions, and seasonal factors.	• Low suitability. • The risk of PFAS bioaccumulation and limited degradation capability makes it less suitable for composting. • The mobilised PFAS could have higher potential to contaminate soil after the use of compost.	[158,159,160]
	Soil flushing and soil washing	• Suitable for sandy soils and clay sands (at increased cost). • Low-technology approach with high potential for land reuse following the removal of the contaminant. • Large quantities of soil can be treated. • Can be applied in situ.	• Expensive. • Long-term operation. • Large initial investment. • Requires excavation. • Low-level concentrations persist in the leachate, requiring significant post-treatment	• Not suitable. • Could adversely affect the compost by disrupting its natural microbial ecosystem, altering the physical structure and moisture content. • Can potentially reduce the overall quality and fertility of the compost.	[161,162,163]
Immobilisation	Sorption and stabilisation	• Amendments used to offer advantages of: ease of application, cost-effectiveness, and commercially available. • No need for off-site management. • Suitable for sandy and clay soils. • Can be applied in situ and ex situ.	• PFAS are not destroyed and left on-site. • Long-term efficiency and stability are unknown. • Costs may increase based on the volume of the absorbent required. • Parameters of the treated material may change, which affects its use.	• Moderate suitability. • Immobilising PFAS, preventing leaching from compost. • PFAS not destroyed may pose long-term risks to compost quality.	[125,126,162,164]

		• Minimal site disturbance. • Cost-effective.			
Destruction	Bioremediation (biological treatment)	• Can be applied ex situ. • Cost-effective. • Sustainable approach. • Simple.	• Little evidence of PFAS biodegradation. • Time-consuming (slow biodegradation of PFAS.). • Requires a specific environment.	• Moderate suitability. • If an effective biological treatment in degrading PFAS, it could be suitable for composting. • However, the slow and uncertain degradation process may affect the composting process and compost quality.	[165,166]
	Thermal treatment	• Suitable for silty or clay soils. • Can be used for managing PFAS in a range of soil types. Existing incineration facilities are well established. • Incineration is a crucial solution for handling PFAS-containing waste.	• Expensive. • Energy-intensive. • Needs a high initial investment in infrastructure. • Not suitable for in situ treatment because of the high temperature required. • Not sustainable, as it can destroy the ecosystem. Pretreatment may be required, increasing time. • Managing the emission of greenhouse gases is challenging.	• Not suitable, due to its high energy requirements and potential for ecosystem damage. • The high temperatures used may destroy organic matter essential for composting.	[162,167,168]

Source control measures are essential in preventing PFAS from entering the composting system, highlighting the importance of proactive strategies. Moreover, biodegradation as a natural attenuation process during composting has not been investigated, suggesting a critical area for future research to understand and potentially utilise microbial processes for PFAS degradation. Among the limited technologies currently practised in the field, the immobilisation of PFAS is considered one of the most cost-effective, viable and efficient ways to remediate contaminated solid matrices. This method is efficient in reducing the leachability and bioavailability of PFAS in soils and biowaste-amendment soil. Though long-term efficiency and stability have not been studied, one study has confirmed the effectiveness of this approach by various sorbents for up to 3 years [128]. Therefore, there is a significant potential for the immobilisation approach to remove PFAS contamination from compost and therefore reduce the PFAS contamination originating from compost application.

9. Conclusions

In the face of escalating challenges due to rapid population growth, urbanisation, and the growing gap between economic growth and environmental sustainability, this literature review concludes with a critical analysis of the composting of MSW as a waste management system. The increasing volume of MSW necessitates the adoption of sustainable waste management technologies. Composting, a waste management approach to recycling organic waste, emerges as a vital solution, contributing to a circular economy and environmental preservation.

This review focuses on the emerging concern of PFAS contaminants in compost, highlighting their potential transfer into soil and through the food chain, posing adverse impacts on human health and the environment. Despite the numerous beneficial uses of compost in agriculture, the presence of PFAS in compost, known for their persistence and potential toxicity, creates new challenges. Published scientific data on the detection and levels of emerging PFAS contaminants in composts are limited, with a recent study reporting these substances ranged between 1.26 and 11.84 μg kg^{-1} on a dry weight basis. These contaminants have been linked to various adverse human health effects, including cancers, kidney disease, and altered development and immune functions, emphasising the need for comprehensive research and regulatory frameworks.

The remediation of PFAS contaminants in compost is vital, given their potential environmental and health impacts. In this context and in the absence of extensive studies on PFAS remediation approaches in compost, this review discussed the potential remediation approaches, highlighting the approaches that may be suitable for use in composts.

The primary intervention at the input stage of the composting system is source control, which involves identifying and minimising PFAS sources. Mobilisation techniques using surfactants and solvents to facilitate the desorption of PFAS for subsequent remediation through phytoremediation or soil washing have shown potential, though these methods may not be ideal due to incomplete PFAS extraction risks. Destruction methods, including thermal treatments and biodegradation, are generally unsuitable for compost due to high temperatures and potential disruption to the composting process. Immobilisation techniques, utilising amendments like activated carbon and biochar, aim to reduce PFAS mobility and bioavailability, making them more suitable for compost, but still presenting long-term risks.

However, there are significant gaps in understanding and assessing the effectiveness and long-term implications of the remediation approaches in composting. Future studies focused on understanding and developing these methods hold promising potential for advancing sustainable waste management. By mitigating PFAS risks while preserving the advantages of composting, such studies could open new avenues for innovative waste treatment solutions and contribute to environmental sustainability.

In summary, while acknowledging the benefits of composting as a waste management approach, research gaps exist in understanding the occurrence, transformation, and mitigation of PFAS in the composting process. Identifying and addressing the stages of composting that contribute most to PFAS accumulation is crucial. This understanding is essential for developing strategies to minimise PFAS release into the environment, thus ensuring sustainable waste management practices in harmony with protecting human health and ecological integrity.

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