BRIEF LITERATURE REVIEW OF THE POTENTIAL SOURCES OF PFAS AND PBDES IN FOOD ORGANICS AND GARDEN ORGANICS COMPOSTS

FINAL REPORT TO NEW SOUTH WALES ENVIRONMENT PROTECTION AUTHORITY FROM WCA

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EXECUTIVE SUMMARY

The New South Wales Environment Protection Authority (NSW EPA) required a brief technical review of literature and other information from across the globe on the potential sources of perfluoroalkyl substances (PFAS) and polybrominated diphenyl ethers (PBDEs) detected in food organic and garden organic (FOGO) and garden organic (GO) composts. The feedstock differences of these materials are thought to potentially influence the concentrations of PFAS and PDBEs present in the composts, specifically with FOGO containing greater concentrations than GO.

The data collected and analysed in the NSW EPA's study[1] into FOGO/GO composts and other recovered organics of PDBEs and PFAS in FOGO and GO are relatively uncommon in the open and grey literature. As such, definitely and unequivocally identifying specific sources of these persistent chemicals in composts is not straight-forward. Therefore, in this review we have assessed the evidence and data for possible and probable sources of PDBEs and PFAS in FOGO and GO.

Sources of PFAS in FOGO composts are likely to be food contact materials (FCMs). Older FCMs (pre-2010) and some recycled materials used in food and beverage containers have been identified as containing considerable quantities of PFAS. The maximum PFAS concentrations determined in the NSW EPA's study in FOGO samples are two-orders of magnitude lower than PFAS concentrations from similar types of organic materials from elsewhere.

Food of animal origin and house dust are the two main sources of human exposure to PBDEs. The presence of PBDEs in food waste from the food material itself and associated household dust were therefore anticipated to be the major sources of PBDEs in FOGO. However, food itself is unlikely to be the primary source of the concentrations of PBDEs observed in FOGO derived compost.

Household dust derived from furniture, textiles and electronic devices is an acknowledged source of PBDEs and it is possible that this is a source of some of the PDBE concentrations measured in compost from FOGO. However, concentrations of PBDE are also elevated in composts from GO, which is not expected to have source materials containing brominated flame retardants.

Further investigation is recommended to confirm the sources of these persistent organic chemicals in FOGO (and to a lesser extent GO) derived composts. An initial scoping survey could be undertaken to attempt to determine whether the primary source of PFAS and PBDEs is in the source material prior to its processing at the compost facilities. This would involve sampling food organics and garden organics immediately following collection. This would establish a more explicit link between the sources of these chemical groups and the NSW FOGO concentrations.

[1] This is referred to as the screening risk assessment

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1 INTRODUCTION

The New South Wales Environment Protection Authority (NSW EPA) engaged wca to undertake a literature search for potential sources of perfluoroalkyl substances (PFAS) and polybrominated diphenyl ethers (PBDEs) detected in food organics and garden organics (FOGO) and garden organics (GO) composts.

1.1 Project objectives

The purpose and objective of the project was to undertake a short, focussed literature review to identify the key potential sources of PFAS and PDBEs in FOGO/GO. The scope of the project included the development of focussed search strings for specific contaminants, covering a wide range of FOGO or GO inputs. The literature identified from the search was then screened and reviewed to reach conclusions on the sources of PFAS and PDBEs.

1.2 Background

NSW EPA previously sampled FOGO compost from 10 facilities across NSW in 2019. This sampling was broadened in 2020/2021 and composts were sampled from 21 sites across metropolitan, regional and rural NSW covering:

- 13 facilities producing food organic and garden organic (FOGO) compost;
- 5 facilities producing garden organic (GO) compost; and
- 3 onsite rapid dehydration food waste units (ORDUs)[2].

Samples of these outputs were analysed for PFAS and PBDEs and a screening risk assessment was undertaken based on scenarios of land application of these composts in NSW. As part of the analyses of the data for this screening risk assessment it was suggested that some of the composts had elevated levels of PFAS and PDBEs relative to other types of recovered organics. Specifically, it appeared that sources of PFOA, PFHxA, and the PDBE congeners Br1-Br9 and Br10 were entering the FOGO waste stream that are not present in the GO waste steamand both groups of compounds were below the limit of reporting or close to it in samples from dehydrated food waste units.

Source separation of recycled materials is generally considered to reduce the propensity for the inclusion of specific contamination sources (e.g. Rigby et al. 2020). However, PFAS and PDBEs have historically been present in a wide-range of industrial and commercial products and are ubiquitous in household and street dusts (Weiss et al. 2021) and food stuffs (EFSA 2012, although food concentrations tend to be generally low[3]). Importantly, while bans and reductions in use may be in place, these chemicals have long residence times in the environment and inevitably will be present in domestic and industrial settings as long as the products of which they are components remain in use.

[2] These ORDUs are located at restaurants and cafes and take post-consumer food (plate scrapings) as well as kitchen preparation food wastes only

[3]https://www1.health.gov.au/internet/main/publishing.nsf/content/2200FE086D480353CA2580C900817CDC/$File/Occurrence-Dietary-Exposure-Literature-Reveiw.pdf

In this brief review we have attempted to identify possible sources of PFAS and PDBEs that may be present in FOGO and/or GO and through the scientific evidence consider probable, or most likely, sources.

1.3 Report structure

In Section 2 we outline the searching strategy used for the information and literature review and provide results of those searches; the review of the findings from this literature search and implications for the potential sources of PFAS and PBDEs are discussed in Section 3. A summary of the findings is given in Section 4 and brief conclusions provided in Section 5. Excel spreadsheets of the results from the open literature searching and screened abstracts are appended to this document.

2 LITERATURE SEARCHING

In this section we detail how the literature search strategy was undertaken to identify relevant publications on the potential sources of PFAS and PDBEs in anticipated inputs to composts including food waste and garden waste as well as in numerous potential additional input materials such as paper, plastic, and wood.

2.1 Search strategy

Searches of published scientific literature were conducted to identify sources that contain details of PFAS or PDBEs concentrations in materials likely to be inputs to FOGO or GO derived compost. The search range covered from 2005 to present, with the searches being conducted using Derwent Innovation[4]. Derwent Innovation is a bibliographic database covering scientific literature from products including Web of Science, Current Contents, Conference Proceedings and Inspec.

Specific search strings were derived to cover PFAS, PFOA PFHxA and PFHxS and PDBEs: Br1-Br9 and Br10 using the technical names, acronyms and where appropriate, registry numbers. The resulting hits from the searches were downloaded into an Excel spreadsheet as a record of the searches, and the titles and abstracts were then screened for potentially relevant papers relating to relevance for the specific project aims. The search strings which were used for the literature search and the number of hits obtained from each database are shown in Table 2.1.

Table 2.1 Search strings and results from literature searches

Search term	Derwent Innovation[1]
(PFAS OR Per- and polyfluoroalkyl substances) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	295
(PFAS OR Per- and polyfluoroalkyl substances) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	14
(335-67-1 OR PFOA OR Pentadecafluorooctanoic Acid) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	432
(335-67-1 OR PFOA OR Pentadecafluorooctanoic Acid) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	7
(307-24-4 OR PFHxA OR Undecafluorohexanoic acid) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	33
(307-24-4 OR PFHxA OR Undecafluorohexanoic acid) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	3
(355-46-4 OR PFHxS OR Perfluorohexanesulfonic acid OR 1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexane-1-sulfonic acid) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	59
(355-46-4 OR PFHxS OR Perfluorohexanesulfonic acid OR 1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexane-1-sulfonic acid) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	1

[4] https://clarivate.com/products/derwent-innovation

Search term	Derwent Innovation[1]
(PDBE OR "polybrominated diphenyl ethers") AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	991
(PDBE OR "polybrominated diphenyl ethers") AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	72
(MonoBDE OR DiBDE OR TriBDE or TetraBDE OR PentaBDE OR HexaBDE OR HeptaBDE or OctaBDE or NonaBDE OR Br1-Br9 OR tetrabromodiphenyl ethers OR pentabromodiphenyl ethers OR hexabromodiphenyl ethers OR heptabromodiphenyl ethers OR octabromodiphenyl ethers OR nonabromodiphenyl ethers OR decabromodiphenyl ether OR 40088-47-9 OR 32534-81-9 OR 36483-60-0 OR 68928-80-3 OR 32536-52-0 OR 63936-56-1) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	200
(MonoBDE OR DiBDE OR TriBDE or TetraBDE OR PentaBDE OR HexaBDE OR HeptaBDE or OctaBDE or NonaBDE OR Br1-Br9 OR tetrabromodiphenyl ethers OR pentabromodiphenyl ethers OR hexabromodiphenyl ethers OR heptabromodiphenyl ethers OR octabromodiphenyl ethers OR nonabromodiphenyl ethers OR decabromodiphenyl ether OR 40088-47-9 OR 32534-81-9 OR 36483-60-0 OR 68928-80-3 OR 32536-52-0 OR 63936-56-1) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	21
(decaBDE OR decabromodiphenyl ether OR Br10 OR 1163-19-5) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Plastic contamination OR Paunch OR Paper OR Carboard OR Digesta)	168
(decaBDE OR decabromodiphenyl ether OR Br10 OR 1163-19-5) AND ("Food waste" OR "Garden waste" OR "Organic waste" OR Sawdust OR wood OR Mulch OR Paunch OR Paper OR Carboard OR Digesta) AND (Plastic)	22

[1]https://clarivate.com/products/derwent-innovation

2.2 Search results

After removing the duplicate references from the initial searches, 651 publications remained for PFAS or PFAS-related substances and 1052 remained for PDBEs and related substances. Initially, the relevance of these papers was screened by title, then by abstract. The screening process was targeted to identify those papers that may include information on the contaminant profile of FOGO or GO derived compost inputs.

From the published literature, 18 papers for PFAS and 27 for PDBE were identified that contained information relevant for further investigation. These papers were obtained and reviewed in detail. Relevant details were extracted and used to complete the project aims.

Grey and regulatory sources were also identified from online searches for the key words or through advice received from wca's network and experience from previous projects.

3 POTENTIAL SOURCES OF PFAS AND PBDEs TO FOGO AND GO

In this section we review the potential sources of PBDEs and PFAS to FOGO and GO, from the evidence collected through the literature searching undertaken in Section 2. From the searches it is clear just a few studies have been undertaken that provide a direct link for diffuse chemical inputs to source separated organic materials. Therefore, for this review we have had to assume good practice and appropriate guidance have been followed in the use of source material. Furthermore, considering the few data showing explicit links for some source materials and composts, we need to consider a reasonable balance of probability when considering sources of PFAS and PBDEs to FOGO.

3.1 Sources of PFAS in FOGO and GO

We have used two semi-quantitative terms to describe the likelihood of the sources of PFAS and PBDEs in the FOGO and GO:

- Possible sources are those that may be responsible for the concentrations of PDBEs and PFAS in the composts, but are not the most likely; and
- Probable sources are those for which there is the existence of a reasonable exposure linkage between the source and the composts. It is this exposure linkage that makes these probable sources.

PFAS are perfluoroalkyl and polyfluoroalkyl substances. This large group of chemicals have been widely manufactured and used in industrial processes and consumer goods since the late 1940s. Specifically, PFAS have been used in a range of domestic consumer products as coatings and films, as well as in aqueous film forming foams (AFFFs) used in firefighting. These man-made chemicals may be broadly described as persistent in the environment, showing little propensity to degrade and resisting biotic and abiotic degradation under environmental conditions. Therefore, with limited pathways for removal, accumulation in environmental matrices such as soil and sediments, might be expected to occur (as occurs with some other persistent man-made industrial chemicals). PFOS and PFOA, and closely related compounds, have been classified as persistent organic pollutants (POPs) under the Stockholm Convention.

3.1.1 Possible sources of PFAS

The identification of potentially greater concentrations and types of PFAS in FOGO compared to GO could perhaps be seen to indicate that food itself is a potential source of these PFAS. Numerous studies have looked at food as a source of PFAS, but this has been from the perspective of human dietary exposure (e.g. EFSA 2011, Denys et al. 2014). Relatively limited general exposure via food sources to the human population have been noted (the EFSA study suggests less than 12% of the 4881 food samples returned quantifiable results, e.g. Ruffle et al. 2020). It is likely that in addition to edible food items, a proportion of the material present

as food waste input to FOGO will be deemed 'nonedible' (peelings, fat, bones, etc.) and for this there are few PFAS data available.

Table 3.1 shows the concentrations of PFOS and PFOA in food stuffs and beverages summarised in a global literature review by Sungur (2017). From the table foodstuffs have relatively low concentrations compared to the food contact materials, which are at the bottom of the table, and show the highest mean concentrations of PFOA identified and the second highest of PFOS. Food contact materials are discussed further below.

Table 3.1 Summary of the levels of PFOA and PFOS in food products and beverages (from: Sungur 2017)

Sample	PFOA (ng g^{-1})	PFOS (ng g^{-1})
Fish		
Min	<0.05	0.05
Max	0.40	45.80
Mean	0.13	10.45
Seafood		
Min	0.07	0.09
Max	7.54	13.90
Mean	2.88	7.18
Meat		
Min	0.05	0.001
Max	12.50	2.60
Mean	2.13	0.75
Cereals		
Min	0.01	0.004
Max	0.02	0.098
Mean	0.02	0.03
Drinking water		
Min	0.005	0.004
Max	0.61	0.043
Mean	0.17	0.016
Milk		
Min	0.02	0.005
Max	0.18	0.695
Mean	0.06	0.186
Egg		
Min	nd	0.40
Max	nd	86.9
Mean	nd	39.3
Vegetables		
Min	0.008	0.005
Max	0.121	0.019
Mean	0.064	0.008
Tea		
Min	0.04	nd
Max	0.25	0.08
Mean	0.14	0.04
Food contact materials		
Min	53.0	12.0
Max	198.0	23.0
Mean	125.5	17.5

Paper sludges and pulps have been identified as sources of PFAS to soils receiving these materials in the infamous Rastatt case, in Germany (Bugsel et al. 2021). The use of PFAS in paper is targeted at making these materials oil and water resistant (hence the use in food contact materials, see below). Bugsel et al. (2021) stress the historic nature of this

contamination source, stressing it was early 2000s and that now the degradation products are the challenge.

Another potential source of PFAS compounds to FOGO could reasonably be assumed to be from 'non-stick' fluorocarbon resin coated cooking utensils and pans. Choi et al. (2018) investigated the release of PFAS from 139 frying pans, 132 baking utensils, 10 grill pans, 10 pots and 10 electric rice cookers in Korea using different leaching solutions to simulate normal kitchen use. The authors noted that only the frying pans released detectable PFAS (PFOA < LOD - 1.64 µg L^{-1}, PFNA < LOD~1.36 µg L^{-1}, PFDoDA, < LOD - 1.85 µg L^{-1}, PFTrDA < LOD - 2.16 µg L^{-1}, PFTeDA < LOD - 1.21 µg L^{-1}, PFHxDA < LOD - 2.54 µg L^{-1} and PFODA < LOD - 3.05 µg L^{-1}). It was noted that PFAS were only released on the first use of the materials, not repeated use and it did not matter which cooking oils or methods were used. However, food preparation items are perhaps not a major source, as indicated by the PFAS data from the dehydration food waste units (ORDUs)(in the NSW screening risk assessment), which were all below LOR.

Perhaps not surprisingly, and reflecting usage in household consumer products, PFOA and PFOS are most commonly detected PFAS in household dusts as shown by Weiss et al. (2021) (Table 3.2). These authors also noted that living spaces showed different characteristic profiles of PFAS, with PFNA and PFDA detected in living rooms, but not other rooms. In a further study on indoor dust and PFAS and their precursors in Finland, Winkens et al. (2018) noted higher dust levels of PFOS in rooms with plastic flooring materials compared to those where the floor was made of wood. Despite this potentially being a source of human exposures to PFAS the direct exposure link from indoor dusts to FOGO is perhaps relatively diffuse, at least compared to dust sources from outdoors (Section 3.2). This later source is unlikely to be as important as other probably PFAS sources (Wood 2021).

Table 3.2 PFAS concentrations determined in household dusts from Sweden (n = 46) (from: Weiss et al. 2021)

	Household dust				
PFAS	>LOD (%)	>LOQ	Mean (ng/g dust)	Median	Min-max
PFBA	11	0	2.0	<LOQ	<LOD-23
PFPeA	7	0	0.93	<LOQ	<LOD-23
PFHxA	96	52	13	6.4	<LOD-99
PFHpA	57	24	5.3	2.2	<LOD-95
PFOA	100	93	51	9.0	<LOQ-650
PFNA	93	54	6.2	3.4	<LOD-44
PFDA	96	52	10	3.2	<LOD-100
PFUnDA	54	17	1.9	1.0	<LOD-22
PFDoDA	41	24	6.5	<LOQ	<LOD-110
PFTrDA	22	4	0.85	<LOQ	<LOD-9.1
PFTeDA	30	17	4.1	<LOQ	<LOD-56
PFBS	2	2	0.19	<LOQ	<LOD-8.7
PFHxS	24	7	0.61	<LOQ	<LOD-8.1
PFHpS	0	0	-	-	
PFOS	100	93	22	13	<LOQ-220
FOSA	0	0	-	-	
6:2 FTSA	65	30	10	1.8	<LOD-220
6:2 PAP	100	87	67	31	<LOQ-460
8:2 PAP	100	93	47	22	<LOQ-360
6:6 PFPIA	39	26	1.0	<LOQ	<LOD-16
6:8 PFPIA	48	33	1.7	<LOQ	<LOD-27
8:8 PFPIA	61	35	0.73	0.10	<LOD-11
6:2 diPAP	100	100	140	65	11-1300
8:2 diPAP	100	100	100	49	7-920
PFHxPA	39	20	3.3	<LOQ	<LOD-31
PFOPA	70	41	47	3.3	<LOD-1800
PFDPA	43	28	8.7	<LOQ	<LOD-70
Σ PFASs			550	280	50-2400

3.1.2 Probable sources PFAS

A recent report undertaken by Wood for the Minnesota Pollution Control Agency investigated the sources of PFAS in recycled organic materials, specifically source separated organic materials (Wood 2021). Key sources of PFAS identified in this work were food contact materials (FCMs), including bakery paper/bags, beverage cups, coffee filters, food paper bags, food paper boxes, food paper wrappers, milk bottles and especially, with PFAS levels 1-4 orders of magnitude greater than the other categories, microwave bags and paper tableware. The most determined PFAS were polyfluoroalkyl substances and more specifically fluorotelomer alcohols and polyfluoroalkyl phosphoric acid esters. Food materials and yard waste was assessed as potential sources of PFAS, and trees and shrubs tended to have greater maximum concentrations than food sources (fish, seafood, eggs, and vegetables), although both these were lower than FCM. As part of the comprehensive study by Wood, data gaps were also highlighted and for FCM specifically, the authors considered that composition of the materials was poorly understood, with a focus on 'use category' (i.e. what the material's function was: e.g. beverage cup, boxes, muffin trays, etc.)

Paper-based FCM have long been identified as a potential diffuse source of PFAS (e.g. Trier et al. 2011) although evidence of transference of PFAS from the FCM to the food is mixed (e.g. Zafeiraki et al. 2014; Zabaleta et al. 2020). What is perhaps more straight-forward is the recognition that FCM consistently contain detectable concentrations of many PFAS while alternatives that are cost-effective, fully biodegradable, and environmentally sustainable are apparently limited (Glenn et al. 2021).

Commonly encountered consumer sources of PFAS were assessed by Kotthoff et al. (2015) and are shown in Table 3.3. Some products, such as the cleaning agents and wood glues contained few detectable PFAS while leather samples, ski waxes, outdoor textiles and some FCM all contained detectable levels of PFAS, with PFOS and PFOA as the main contributors to the total PFAS load. The authors noted that for FCM, three older paper-based materials (pre-2010) contained the highest levels of PFHxA, PFOA and PFDA of 183, 658 and 489 µg kg^{-1}, respectively. The most frequently and abundantly detected substances in the FCM samples (n = 39) were PFOS, PFBA and PFPA.

Table 3.3 Measured PFAS concentrations in consumer products, including FCMs, values in µg kg^{-1}, aside from outdoor textiles, carpet, leather, and awning cloth which are µg m^{-2} (from: Kotthoff et al. 2015).

	Cleaner		Wood glue		Nanosprays and impregnation sprays		Outdoor textiles		Carpet		Gloves		Paper-based FCM		Ski wax		Leather		Awning cloth	
	Max	Median	Max	Median	Max	Median	Max	Median	Max	Median	Max	Median	Max	Median	Max	Median	Max	Max	Max	Median
PFBA	-:-	-:-	-:-	-:-	2.5	1.4	6.1	0.5	14.7	-:-	1.2	0.8	9.9	0.7	362.1	14.3	241.8	241.8	0.5	0.5
PFPA	-:-	-:-	-:-	-:-	-:-	-:-	39.7	2.3	4.4	1.4	76.1	3.1	33.3	15.4	440.3	18.6	197.0	197.0	8.5	5.8
PFHxA	-:-	-:-	-:-	-:-	14.1	6.9	17.1	1.5	0.8	-:-	2.6	1.3	182.8	1.4	1737.1	17.9	4.5	4.5	1.0	0.9
PFHpA	-:-	-:-	-:-	-:-	4.2	2.7	4.6	-:-	1.4	-:-	1.3	0.6	379.3	-:-	424.8	7.6	1.6	1.6	-:-	-:-
PFOA	1.1	0.7	-:-	-:-	28.9	15.9	41.0	6.0	1.1	-:-	15.9	9.3	658.1	3.2	2033.1	15.5	12.4	12.4	10.9	5.8
PFNA	-:-	-:-	-:-	-:-	8.0	2.8	8.3	1.0	1.2	-:-	5.7	2.9	478.2	0.5	678.0	10.7	1.9	1.9	3.9	3.7
PFDA	-:-	-:-	-:-	-:-	10.7	8.1	12.6	2.6	1.0	-:-	10.2	5.7	489.4	2.5	1840.5	22.6	0.9	0.9	-:-	-:-
PFUnA	-:-	-:-	-:-	-:-	3.8	1.4	4.0	0.5	0.5	-:-	3.0	1.5	306.7	-:-	411.5	6.2	0.6	0.6	1.4	-:-
PFDoA	-:-	-:-	-:-	-:-	5.3	3.5	8.4	1.4	1.3	-:-	10.2	5.3	244.4	2.0	1441.9	16.1	3.6	3.6	1.4	1.4
PFTrA	-:-	-:-	-:-	-:-	1.2	0.5	1.5	-:-	-:-	-:-	4.5	2.0	36.6	-:-	179.4	4.0	0.9	0.9	0.8	0.8
PFTeA	0.8	-:-	-:-	-:-	1.9	1.1	8.8	0.7	1.1	-:-	24.8	10.1	22.1	1.3	745.2	9.8	1.4	1.4	0.9	0.8
PFBS	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	26.8	-:-	2.0	0.5	-:-	-:-	3.1	-:-	143	143	-:-	-:-
PFHxS	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	0.6	-:-	9.3	-:-	10.1	10.1	-:-	-:-
PFHpS	-:-	-:-	-:-	-:-	-:-	-:-	0.3	-:-	-:-	-:-	-:-	-:-	0.8	-:-	5.3	-:-	1.3	1.3	-:-	-:-
PFOS	1.6	1.2	-:-	-:-	-:-	-:-	35.4	9.5	2.9	1.0	11.9	1.5	8.8	0.7	159.8	1.6	5.6	5.6	2.3	1.1
PFDS	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	1.7	-:-	1.3	-:-	0.7	0.7	-:-	-:-
FTOH 4:2	-:-	-:-	~	~	329,000	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	-:-	~	~	~	~	~	~

-:- below limit of quantification, ~ no samples were analysed

A further study on the significance of PFAS in food contact materials by Curtzwiler et al. (2020) suggested that these substances were being added to paper-based packaging materials unintentionally, the source being residues from recycled fibre and paperboard used in manufacturing. Indeed, advocating for the cessation in single usage plastics cups, while increasing the use of recycled materials, may increase PFAS levels in composted materials receiving this feedstock.

Despite cessation of use and import of PFAS, these non-intentionally added substances are thought to enter the markets (in the USA) through imports, in both virgin and recycled fibre feedstocks (e.g. Monge Brenes et al. 2019). It is inevitable that if found in compostable FCMs and foodware, that PFAS will be present in composts (Schaider et al. 2017). Nevertheless, there are data that demonstrate the direct linkage between source separated compost PFAS concentrations and FCMs, as illustrated in the schematic in Figure 3.1[5][6][7]. A partly relevant

[5] E.g. https://www.mcgill.ca/mjsdl/article/pfas-food-contact-materials-consequences-human-health-compost-and-food-chain-and-prospects#_ftnref17
[6] https://www.biocycle.net/pfas-organic-residuals-management/
[7] https://www.pca.state.mn.us/sites/default/files/w-sw4-37.pdf

study by Choi et al. (2019) on ten samples of the organic fraction of municipal solid waste, which is equivalent to MWOO, noted PFAA loads ranged from 28.7 to 75.9 µg kg^{-1} when the compost included FCM and from 2.38 to 7.60 µg kg^{-1} for composts that did not. The majority of PFAS in the composts were shorter chain PFAAs (six or fewer carbons are perfluorinated) and PFOS and PFOA were detected in all ten composts.

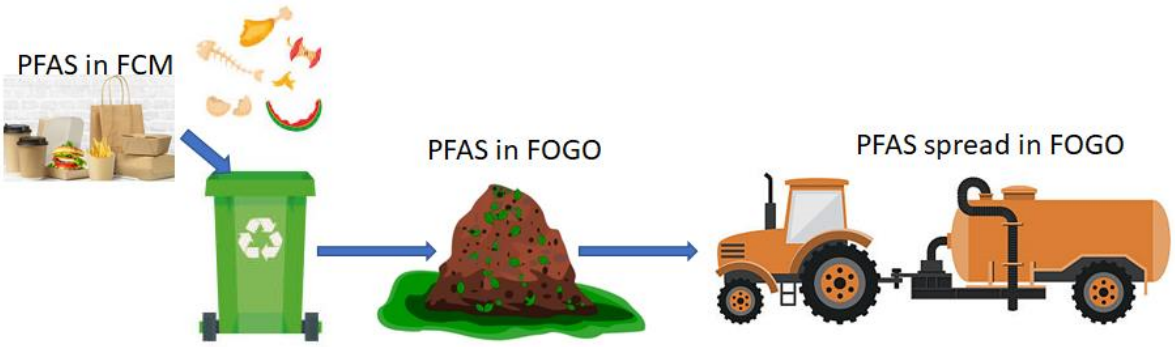

Figure 3.1 Link between food contact materials (FCM) and PFAS in FOGO (e.g. Choi et al. 2019)

3.2 Sources of PDBEs in FOGO and GO

Polybrominated diphenyl ethers (PBDEs) are a class of flame retardant that have been used to meet fire safety regulations for fabrics, furnishings, plastics for electronics, computer and television casings and vehicles since the 1970s (Schecter et al. 2008; Bramwell et al. 2016a). PBDEs are additive flame retardants, meaning that they are mixed into plastics or foam without forming chemical bonds; they can therefore diffuse out of these products into the environment and subsequently enter the food chain by various pathways during production, use and disposal (Bramwell et al. 2016b; Lopez et al. 2018)

PBDEs are persistent, undergo long range transportation and have been found throughout environmental compartments and in food chains across the globe (Bramwell et al. 2016a). The use of pentaBDE (Br-5) and octaBDE (Br-8) technical products was formally banned in all applications for the EU market from August 2004, and importation or manufacture in Australia has not been permitted since 2007[8]; these two products were added to the Stockholm Convention's list of persistent organic pollutants (POPs) for elimination in 2009. Environmental and dietary levels of the BDEs in these products have declined since their banning but their persistence and bioaccumulation mean that they are still present in the environment and specifically in lipid-rich materials. Tetra- (Br-4), hexa- (Br-6), hepta- (Br-7) and deca- (Br-10) BDEs have been more recently added to Annex A (Elimination) of the Stockholm Convention

[8] https://www.environment.gov.au/system/files/resources/8e81d7e1-a379-4590-b296-19e14a72d909/files/factsheet.pdf

and deca-BDE was subjected to an EU Restriction in 2019 limiting its use to 0.1% by weight. As for PFAS above, the following subsections detail possible and probably sources of PBDE in compost output, and specifically FOGO.

3.2.1 Possible sources of PDBEs

During the use and lifetime of a product containing PBDEs, they can be released into indoor air and dusts (Bramwell et al. 2016b; He et al. 2018; Stasinska et al. 2013). In a study of residential dust samples from Western Australia, Stasinska et al. (2013) detected PBDEs in all samples with the sum of the most common PBDEs (BDEs 47, 99, 100, 153, 183 and 209) ranging from 60.4 to 82,400 ng g^{-1}. He et al. (2018) measured median concentrations for 8 BDEs (28, 47, 99, 100, 153, 154, 183 and 209) of 2.1 mg g^{-1} in dust and 0.049 ng m^{-3} in indoor air in Australian indoor environments (offices, houses, hotels and public transport in Brisbane and Canberra). He et al. (2018) found that the BDE occurring at the highest concentration was Br-10 (BDE 209), generally at concentrations of 1-10 µg g^{-1}.

PBDEs in household dust have been studied primarily from the view of determining human exposure and there are no data indicating the amount of dust that could be associated with food or food waste. Bramwell et al. (2016b) state that deposition of dusts containing PBDEs onto food can occur during processing or in the place of food consumption; the same paper suggests that PBDE in food may also be the result of processing or packaging, but no data were identified on the levels of PBDEs in food packaging.

Where there is a source of wood to GO derived composts there is the potential for the presence of engineered wood composites which may contain PBDEs (Ulker and Ulker 2019).

3.2.2 Probable sources PDBEs

PBDEs bioaccumulate in a similar way to persistent organic pollutants (POPs) such as PCBs and dioxins, meaning that fatty food products of animal origin are expected to be the major contributors to dietary intake, being almost entirely present in the fat fraction of the foodstuffs (Bakker et al. 2008). It is therefore anticipated that this will be reflected in the food waste input to the generation of FOGO. PBDEs are resistant to degradation so are unlikely to be broken down in the composting process.

Numerous diet surveys have measured concentrations of PBDEs in various food stuffs and a summary of these is detailed below. However, it is difficult to compare PBDE data from different studies as they invariably use a different subset of BDEs, e.g. the 'EC 10' PBDEs (BDEs 28, 47, 49, 99, 100, 138, 153, 154, 183, 209) commonly analysed for in food surveys, a wider range of 17 PBDE congeners (BDEs 17, 28, 47, 49, 66, 71, 77, 85, 99, 100, 119, 126, 138, 153, 154, 183 and 209), small subsets of this or even larger analytical suites such as the one used in the FOGO and GO screening risk assessment.

Bakker et al. (2008) detail a diet study from the Netherlands, in which they report total PBDEs as the sum of BDEs 47, 99, 100, 153, 155 (NB. excluding BDE 209, Br-10):

- Fish and crustaceans: 10 – 4,810 ng kg^{-1} 'total PBDEs';
- Meat: 49-113 ng kg^{-1};

- Milk and dairy: 31-280 ng kg^{-1};
- Eggs: 71 ng kg^{-1}; and
- Oils and fats: 82-110 ng kg^{-1}

Kantiani et al. (2010) undertook a review of emerging contaminants in food and reported PBDE concentrations of 18-955 ng kg^{-1} in butter (for BDEs 17, 28, 47, 66, 71, 85, 99, 100, 138, 153, 154, 183 and 190) and 135-604 ug kg^{-1} for 27 unspecified PBDE congeners in fish and crabs.

In an Irish food study Lopez et al. (2018) reported that the most abundant and frequently occurring congeners were BDE-47, BDE-49, BDE-99, BDE-100 and BDE-209 with the highest concentrations found in fish, fat and eggs. Mean summed EC10 PBDE concentrations for a variety of foodstuffs are detailed below:

- Eggs: 0.38 ug kg^{-1};
- Fat: 0.26 ug kg^{-1};
- Fish: 0.56 ug kg^{-1};
- Milk: 0.02 ug kg^{-1}; and
- Liver: 0.01 ug kg^{-1}

Schecter et al. (2008) reported that US studies showed somewhat higher levels of PBDEs than reported elsewhere (measuring BDEs 17, 28, 47, 66, 77, 85, 99, 100, 138, 153, 154, 183 and frequently BDE 209), although the data are comparable to that reported in other studies retrieved from the literature search. Fish were considered the most highly contaminated (median 616 ng kg^{-1}), then meat (median 190 ng kg^{-1}) and dairy products (median 32.2 ng kg^{-1}).

The UK Food and Environment Research Agency (FERA 2015) undertook an investigation into brominated flame retardants in food and reported the following mean concentrations for EC10 PBDE concentrations in a range of commonly consumed foods:

- Eggs: 0.14 ug kg^{-1};
- Fish: 2.05 ug kg^{-1};
- Processed Meat: 0.19 ug kg^{-1};
- Dairy products: 0.09 ug kg^{-1};
- Shellfish: 0.43 ug kg^{-1};
- Meat: 0.19 ug kg^{-1}; and
- Processed foods: 0.92 ug kg^{-1}

A survey of PBDEs in Australian food (FSANZ 2007) reported the following mean concentrations for total PBDEs based on 26 individual congeners. These data indicate that concentrations of PBDEs in Australian food are broadly comparable to measurements from other parts of the world such as the UK.

- Eggs: 0.93 ug kg^{-1};
- Fish: 0.19 ug kg^{-1};
- Processed meat (bacon): 0.54 ug kg^{-1};
- Dairy products (cheese): 0.19 ug kg^{-1};
- Meat (pork chops): 0.70 ug kg^{-1};
- Butter: 0.27 ug kg^{-1}; and

- Milk chocolate: 0.34 ug kg^{-1}

4 SUMMARY

There is evidence to identify sources of PFAS and PDBEs in FOGO, as compared to GO. PFAS are found in many consumer and industrial products and because many of these have relatively long service lives, reductions, restrictions and bans of some PFAS will inevitably take some time to result in a reduction in domestic and industrial wastes. Possible sources of PFAS to FOGO could be directly from industrial sources but are more likely from diffuse domestic materials and products, including cooking materials, dusts from houses and proofings and coatings on outdoor clothing materials and awnings (Table 3.3).

Food items are unlikely to be sources. The most probable source of PFAS in FOGO is FCM (including disposable food compost bags, Choi et al. 2019), and especially older (pre 2011) stock materials, that are recycled with the food wastes. Importantly, mixtures of PFAS used on some packaging are considered to be proprietary and so do not have to be disclosed by manufactures and some manufacturers are seemingly unaware that their products contain PFAS. Table 4.1 shows data from a recent global literature review by Wood et al. (2021) of selected PFAS concentrations in source separated organic material (SSOM) and yard waste. We are not entirely clear that the data from Choi et al. (2019) shown in the table are source separated materials, and so this column should be viewed with caution regarding the relevance to the Australian situation. There are relatively few PFAS data available for source separated organic materials as compared with non-source separated materials (e.g. Rigby et al. 2020). Further, Wood themselves make a point of stating that intercomparison between composting operations should be undertaken with caution due the variability in feedstocks (for example some allowing the inclusion of compostable FCM, but others not). From Table 4.1 it can be seen from the Wood survey that the maximum concentrations of PFHxA, PFOA, PFOS and PFHxS are all two orders of magnitude greater than the maxima identified in the FOGO and GO from the NSW EPA's study. Table 4.1 also shows that while maximum concentrations of PFOA and PFHxA are factors of 2 and 100 greater in the source separated materials, respectively, PFOS and PFHxS maxima are greater in the yard wastes (but by factors of between 2 and 1.6).

Table 4.1 Concentrations of selected PFAS in source separated organic material (SSOM) and yard waste. Note the units are parts per trillion (ng kg^{-1})(from: Wood et al. 2021)

Type	PFAS Analyte	Concentration range in Wood, 2019. Evaluation of PFAS at		Concentration range in Choi et al., 2019. PFAA Characterization		Concentration range in literature (ppt)		Other Notables in Literature
		Min detected concentration	Max detected concentration	Min detected concentration	Max detected concentration	Min detected concentration	Max detected concentration	
SSOM	Perfluorocarboxylic acids							
	PFBA	30,600	2,060,000 J	2,810	12,040	1.3	13,450	Min- Vegetables (China) and Max- Banana (Poland)
	PFPeA	15,400	780,000	2,660	8,590	0.69	236,000	Min- Vegetables (China) and Max- Lettuce (municipal soil)
	PFHxA	44900 J	3,440,000	10,520	49,840	0.28	254,500	Min- Vegetables (China) and Max- Microwave popcorn bag
	PFHpA	6,150	61,400	2,560	2,560	1	2000	Min- Chicken (Netherlands) and Max- Microwave popcorn bag
	PFOA	6,390	133,000	2,540	10,310	0.21	290,000	Min- Vegetables (China) and Max- Popcorn bag
	PFNA	6,770	13,700	120	1,050	0.52	6,800	Min- Whole Egg (China) and Max- Smelt (Lake Ontario)
	PFDA	8,200	25,800	1,070	4,430	1	28,250	Min-Milk and Bakery (Netherlands) and Max- Food Wrappers (Spain)
	Perfluorosulfonic acids							
	PFBS	6,750	57,300	790	7,630	5.7	205,200	Min- Vegetables (China) and Max- Lettuce (industrial site US)
	PFHxS	6480 J	153,000 J	80	250	0.28	1,940	Min- Whole Egg (China) and Max- Milk (Clovis NM)
	PFOS	6,700	3,070,000 J	350	1,530	0.17	387,000	Min- Lettuce (Norway) and Max- Oyster (Gulf of Mex/ChesapeakeBay)
Yard Waste								
	Perfluorocarboxylic acids							
	PFBA	29,000	574,000	150	640	10,000	49,000	Min- Plane Tree (China) and Max- Pine Needles (China)
	PFPeA	28,700	38,500	410	1,430	NA	NA	
	PFHxA	7,140	31,300	380	1,070	2,600	12,000	Min- Willow (China) and Max - Poplar and Gingko (China)
	PFOA	20,300	64,600	40	1,050	2,800	700,000	Min- Poplar and Gingko (China) and Max - tree Leaf (Little Hocking, OH)
	Perfluorosulfonic acids							
	PFBS	16,900	50,200	ND	ND	2,100	17,000	Min- Poplar and Gingko (China) and Max-Pine Needles (China)
	PFHxS	9,780 J	249,000	70	190	5,000	5,000	Min and Max- Poplar and Gingko (China)
	PFOS	6,580 J	7,790,000	470	1,690	1,600	19,000	Min- Poplar and Gingko (China) and Max-Cyprus (China)

Note: Only those detected concentrations in the Wood 2019 Report are presented here and compared to Literature. Other PFAS were analyzed as part of the Wood 2019 report but were not detected.

For PFAS, source characterisation and profiling of chemical constituents (effectively 'finger printing') has been recently used to identify specific pollutant sources. Langberg et al (2020) used the emission characteristics of PFAS from a paper products factory and from a fire station to identify the key source of PFAS to lake sediments in Norway. The paper factory emissions were of PFOS, PFOS precursors (preFOS and SAmPAP), long chained fluorotelomer sulfonates (FTS), and perfluoroalkyl carboxylic acids (PFCA), whereas the firefighting foams were mostly of eight carbon perfluoroalkyl sulfonic acid (PFSA), perfluorooctanesulfonic acid (PFOS). The lake sediments and biota contained chemical profiles that matched the paper products factory. Kibbey et al. (2020) successfully used supervised machine learning to identify the sources of PFAS contamination based on a dataset of previously measured environmental samples. The use of these techniques was driven by the desire to distinguish between fire foam sources and manufacturing sources of PFAS as samples contaminated by specific formulation will fall within a limited range of possible chemical profiles, and as such can be identified through the machine learning pattern recognition. It may be possible to use such profiling techniques to assist in narrowing the spectrum of potential PFAS sources in organic materials, specifically as there is some understanding of the likely characteristic profile of the PFAS from composted FCM (Choi et al. 2019).

The FOGO samples from the NSW dataset contain considerably higher concentrations of PBDEs than the GO samples, approximately ten times higher (excluding GO samples from site O). This indicates that there is a source of PBDEs in the FOGO that is not present in the GO. It was initially considered that this was likely to be the food waste itself but from the available evidence very low concentrations of PBDEs were detected in the dehydrated food waste. The PBDE concentrations in the NSW FOGO are much higher than those previously reported in food samples from Australia and around the world, i.e. FOGO contains ~40 ug kg^{-1} total PBDEs, whereas even the most contaminated foodstuffs such as meat and fish generally contains PBDE concentrations about 2 orders of magnitude lower, typically ≤0.4 ug kg^{-1}. Partial dehydration during composting could result in an increase in concentration in comparison to wet weight food but this does not explain the levels of PBDEs measured in FOGO-derived compost.

A recent review of studies relating to the US population, concluded dietary exposure did not explain the current PDBE body burdens, and exposure to house dust was estimated to account for 82% of the overall estimated intake (from FSANZ 2007). It is therefore possible dust from residential properties, and possibly compost processing facilities, is contributing the bulk of the measured PBDEs; however, this requires further investigation before it can be accepted as an explanation for the elevated PBDE concentrations determined in FOGO derived compost. It should be noted that PBDE concentrations in GO derived composts are an order of magnitude higher than those observed in food surveys despite the lack of lipid-rich material or potential input of PBDE-containing dust in GO; this suggests that there may be a currently unexplained source of PBDEs or a contribution from the processing facilities that could serve as a source of PBDEs in both GO and FOGO derived composts. Compost from Facility O, processing GO, contained extremely high levels of PBDEs and it is considered likely that a source material such as engineered wood composite may have been accidentally added to the garden organics processed at this facility.

5 CONCLUSIONS

Possible sources of PFAS in FOGO composts are many, including food material (including from utensils use), household dusts, and coated fabrics. However, probable sources to FOGO are more likely to be food contact materials (FCMs). Older FCMs (pre-2010) and some recycled materials used in food and beverage containers have been identified as containing considerable quantities of PFAS. Composts with and without FCM feedstocks have been shown to differ in PFAS content, especially short-chain compounds (six or fewer carbons are perfluorinated), by an order of magnitude. A comparison between the maximum concentrations from the NSW EPA FOGO samples with similar organic materials shows the values found in NSW to be two-orders of magnitude lower.

It is generally considered that food of animal origin and house dust are the two main sources of human exposure to PBDEs (e.g. Pietron and Malagocki 2017). The presence of PBDEs in food waste from the food material itself and associated household dust were therefore anticipated to be the major sources of PBDEs in FOGO. However, typical concentrations of PBDEs measured in food surveys and the extremely low levels detected in dehydrated food waste, indicate that food itself is unlikely to be the primary source of the concentrations of PBDEs observed in FOGO derived compost.

Household dust derived from furniture, textiles and electronic devices is an acknowledged source of PBDEs and it is possible that this is a source of some of the PDBE concentrations measured in compost from FOGO. However, concentrations of PBDE are also higher than expected in composts from GO, which is not expected to have source materials containing brominated flame retardants. They may therefore also be a contribution from dust generated in the FOGO and GO processing facilities. Where there is a source of wood to GO derived composts there is the potential for the presence of engineered wood composites which may contain brominated flame retardants such as PBDEs (Ulker and Ulker 2019).

For both groups of substances there is difficulty comparing data between different studies as invariably different subsets of BDEs or PFAS are commonly analysed for in food and organic waste surveys.

Further investigation is recommended to confirm the sources of these persistent organic pollutants in FOGO (and to a lesser extent GO) derived composts. An initial scoping survey could be undertaken to attempt to determine whether the primary source of PFAS and PBDEs is in the source material prior to its processing at the compost facilities. This would involve sampling food organics and garden organics immediately following collection. This would establish a more explicit link between the sources of these chemical groups and the NSW FOGO concentrations, although this can be an arduous and 'unpleasant' task[9].

[9] E.g. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291754/scho1209brqg-e-e.pdf

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ANNEX

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