



Application of the Key Characteristics of Carcinogens to PFAS

Alexis Temkin, Ph.D
Environmental Working Group
Center for PFAS and Cancer (CPAC) Joint Virtual Symposium
Thursday, March 7, 2024

Temkin et al. 2020. Application of the Key Characteristics of Carcinogens to Per and Polyfluoroalkyl Substances. *International Journal of Environmental Research and Public Health*. 17, 1668

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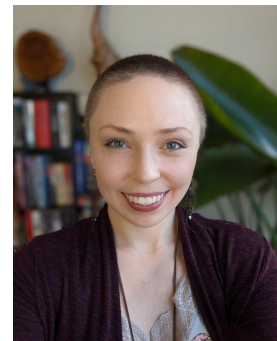
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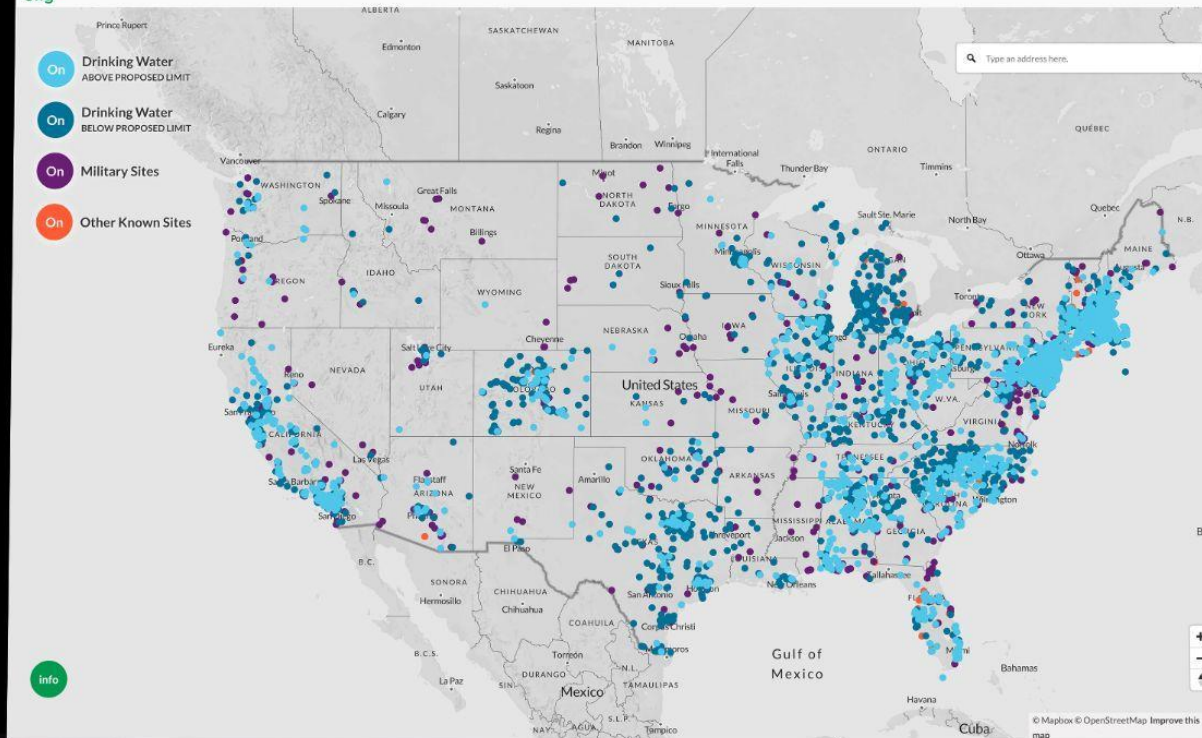
PFAS Contamination in the U.S. (February 5, 2024)



- ☒ Drinking Water ABOVE PROPOSED LIMIT
- ☒ Drinking Water BELOW PROPOSED LIMIT
- ☒ Military Sites
- ☒ Other Known Sites

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The PFAS Problem(s)

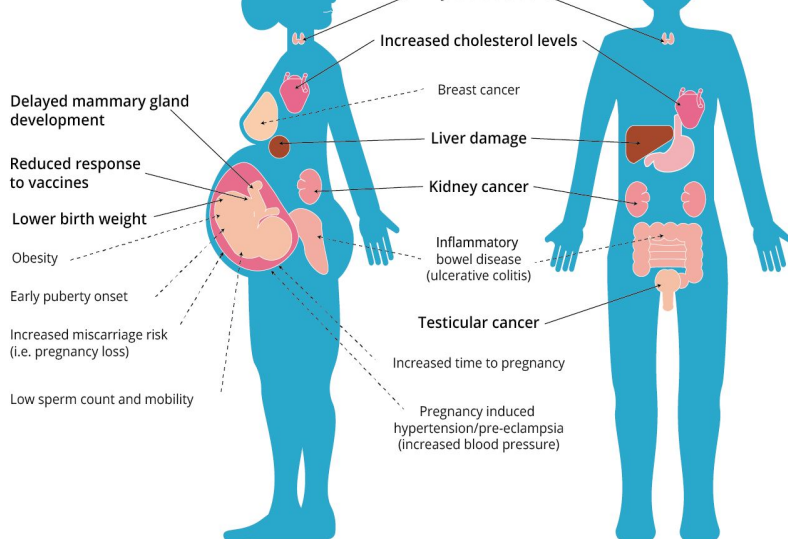
- Widespread global contamination from broad range of uses, industrial dischargers and transport
- Highly persistent and mobile chemicals
- **Growing number of health concerns associated with PFAS exposure**
- **Huge chemical class**



Health Effects of PFAS Exposure

— High certainty
 ---- Lower certainty

Developmental effects affecting the unborn child



Health harms associated with long-chain and short-chain PFAS commonly detected in drinking water and used in consumer or industrial products

Chemical	Harm to the immune system	Harm to development and reproduction	Harm to the endocrine system	Metabolic changes	Changes in the liver	Increased risk of cancer
	Weaker immune response; lower antibody production in response to vaccination; increased allergic response; increased risk of asthma; changes in spleen and thymus	Reduced birth weight; pregnancy-induced hypertension; preeclampsia; reduced fertility; reduced duration of breastfeeding; altered mammary gland development; harm to the male reproductive system	Changes in hormone levels, including thyroid and reproductive hormones; thyroid disease; hormone receptor activation	Increased cholesterol and lipids; weight gain; diabetes	Increased liver weight; changes in liver enzymes	Increased risk of testicular, kidney or breast cancer; increased tumors in laboratory animals; evidence of one or more of the key characteristics of carcinogens
Long-chain PFAS						
PFOA [#]	■	■	■	■	■	■
PFOS [#]	■	■	■	■	■	■
PFNA [#]	■	■	■	■	■	●
PFHxS [#]	■	■	■	●	■	●
PFDA [#]	■	■	■	■	■	●
PFDoA [#]	●	●	●	▲	■	●
PFUA [#]	●	■	●	▲	■	●

Sources: US National Toxicology Program (2016); C8 Health Project Reports (2012); WHO IARC (2017); Barry et al. (2013); Fenton et al. (2009); and White et al. (2011) apud Emerging chemical risks in Europe — "PFAS".

The Key Characteristics of Carcinogens

- Characteristics to organize and integrate evidence for chemical hazard identification
- Born out of analysis of known human carcinogens classified by IARC
- Focus on mechanistic data, but evidence can come from epidemiology, animal bioassays, and *in vitro*/NAMs
- Intentionally broad, and less specific than AOPs or MOA frameworks to improve risk assessment

Smith et al. (2016) *Environmental Health Perspectives*. 124(6): 713-721

Guyton et al. (2018) *Chemical Research and Toxicology*. 31(12):1290-1292

Smith et al. (2020) *Cancer Epidemiology, Biomarkers & Prevention*. 29(10):1887-1903



The Key Characteristics of Carcinogens

Key Characteristics	Examples of Relevant Evidence
1—Is electrophilic or can be metabolically activated	Parent compound or metabolite with an electrophilic structure (e.g., epoxide, quinone, etc.), formation of DNA and protein adducts
2—Is genotoxic	DNA damage (DNA strand breaks, DNA-protein cross-links, unscheduled DNA synthesis), intercalation, gene mutations, cytogenetic changes (e.g., chromosome aberrations, micronuclei)
3—Alters DNA repair or causes genomic instability	Alterations of DNA replication or repair (e.g., topoisomerase II, base-excision or double-strand break repair)
4—Induces epigenetic alterations	DNA methylation, histone modification, microRNAs
5—Induces oxidative stress	Oxygen radicals, oxidative stress, oxidative damage to macromolecules (e.g., DNA, lipids)
6—Induces chronic inflammation	Elevated white blood cells, myeloperoxidase activity, altered cytokine and/or chemokine production
7—Is immunosuppressive	Decreased immunosurveillance, immune system dysfunction
8—Modulates receptor-mediated effects	Receptor in/activation (e.g., ER, PPAR, AhR) or modulation of endogenous ligands (including hormones)
9—Causes immortalization	Inhibition of senescence, cell transformation
10—Alters cell proliferation, cell death or nutrient supply	Increased proliferation, decreased apoptosis, changes in growth factors, energetics and signaling pathways related to cellular replication or cell-cycle control, angiogenesis

Applying the KC Framework to PFAS

Study Objective:

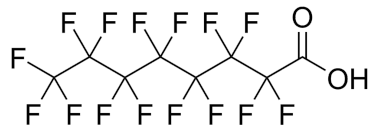
Assemble, organize and evaluate the literature on PFAS through the lens of the key characteristics of carcinogens

Methods:

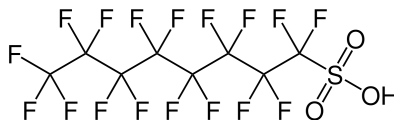
- Selected 26 PFAS
- Literature search of existing reviews supplemented with peer-reviewed articles
- Epidemiology, animal bioassay and mechanistic data
- Strength of evidence assessment

The 26 PFAS we focused on from a huge chemical class

	Perfluoroalkyl carboxylic acid
Long Chain	PFOA, PFNA, PFDA, PFUnA, PFDaA, PFTrDA, PFTeDA
Short Chain	PFHxA, PFBA, PFPeA, PFHpA



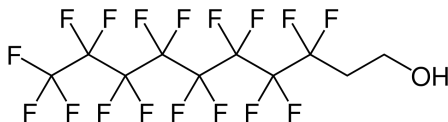
	Perfluoroalkane sulfonic acid/sulfonamid
Long Chain	PFOS, PFHxS, PFOSA*
Short Chain	PFBS



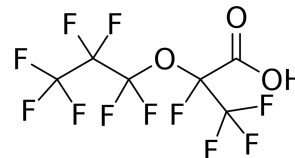
	Polyfluoroalkyl phosphate ester
Long Chain	8:2 monoPAP, 8:2 diPAP, 8:2 triPAP, 10:2 diPAP
Short Chain	4:2 diPAP, 6:2 diPAP



	Fluorotelomer alcohol
Long Chain	8:2 FTOH
Short Chain	4:2 FTOH, 6:2 FTOH



	Fluorinated ether carboxylate
Short Chain	GenX (HFPO-DA); PMOH, PMPP/ADONA



Major Findings:

- Multiple PFAS exhibit several key characteristics of carcinogens
- Many data gaps
- PFOA and PFOS exhibit up to 5 KCS
- KCs 4, 5, 7, 8 and 10 have the strongest evidence
 - 4 - epigenetic alterations
 - 5 - oxidative stress
 - 7 - immune suppression
 - 8 - receptor-mediated effects
 - 10 - cell proliferation



Multiple PFAS exhibit several key characteristics of carcinogens

Key Characteristics	PFOA	PFOS and Long-chain PFAS	Short-chain PFAS	Examples of Relevant Evidence
1—Is electrophilic or can be metabolically activated	PFOA	PFOS, PFHxS, PFNA, PFDA, PFUnA, PFDoA, PFOSA, 8:2 FTOH*, 8:2 diPAP*, 10:2 diPAP	PFBS, PFHxA, PFBA, PFHpA, GenX, 6:2FTOH*, 4:2 diPAP*, 6:2 diPAP	PFAS are quite stable with long half-lives
2—Is genotoxic	PFOA	PFOS, PFNA, PFDA, PFHxS	PFHxA, GenX, PFBS	PFAS are not directly mutagenic; Evidence of DNA damage in some assays likely from secondary event such as oxidative damage
3—Alters DNA repair or causes genomic instability	Data gap	Data gap	Data gap	Data gap
4—Induces epigenetic alterations	PFOA	PFOS, PFHxS, PFNA, PFUnA	Data gap	Observations of differentially methylated regions and changes in global methylation in human cohorts, and <i>in vitro</i> assays
5—Induces oxidative stress	PFOA	PFOS, PFHxS, PFNA, PFDA, PFUnA, PFDoA, PFTrDA, PFTeDA, PFOSA	PFBS, PFHxA, PFPeA	Evidence primarily from <i>in vivo</i> and <i>in vitro</i> assays investigating ROS levels, lipid peroxidation, antioxidant enzymes, etc.

No association

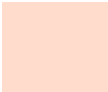
Somewhat suggestive evidence

Suggestive evidence

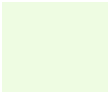
Strong evidence

Multiple PFAS exhibit several key characteristics of carcinogens

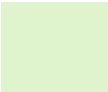
Key Characteristics	PFOA	PFOS and Long-chain PFAS	Short-chain PFAS	Examples of Relevant Evidence
6—Induces chronic inflammation	PFOA	PFOA, PFOS, PFHxS, PFDA, PFUnA, 8:2 FTOH	PFBS	Associations with disease characterized by chronic inflammation, measurements of proinflammatory cytokines <i>in vivo</i> and <i>in vitro</i>
7—Is immunosuppressive	PFOA	PFOS, PFHxS, PFNA, PFDA, PFOSA, 8:2 FTOH	PFBS	Reduced vaccine response in humans, decreased T cell-dependent antibody response in animals, changes in immune cell populations
8—Modulates receptor-mediated effects	PFOA	PFOS, PFHxS, PFNA, PFDA, PFUnA, PFDoA, PFTrDA, PFTeDA, 8:2 FTOH, 8:2 monoPAP, 8:2 diPAP, 8:2 triPAP, 10:2 diPAP	PFBS, PFHxA, PFBA, PFPeA, PFHpA, GenX, ADONA, 4:2 FTOH, 6:2 FTOH	Evidence of binding to several nuclear receptors especially PPARα, changes in circulating hormones and hormone mediated effects in humans and animals
9—Causes immortalization	Data gap	Data gap	Data gap	Some studies on telomere length
10—Alters cell proliferation, cell death or nutrient supply	PFOA	PFOS, PFHxS, PFNA, 8:2 FTOH	PFBS, PFHxA, 6:2 FTOH	Increases in proliferation, migration and invasion in cancer cell lines, cell cycle disruption



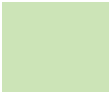
No association



Somewhat suggestive evidence

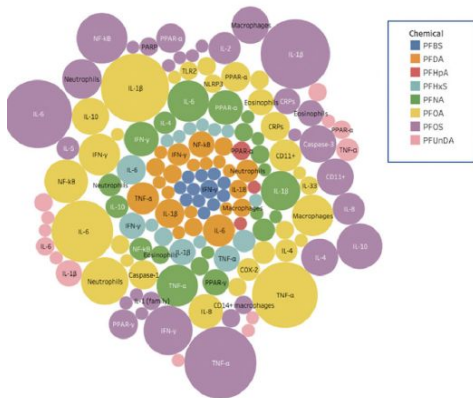


Suggestive evidence



Strong evidence

a. Inflammation



This network diagram illustrates the complex interactions between various immune cell populations and their associated functions. The nodes, represented by colored circles of varying sizes, are labeled with cell types and functions. The connections between nodes represent the relationships and interactions within the immune system. Key clusters include:

- Antibody Production:** Nodes like "Antibody production", "Antibody activity", and "Antibody production" are interconnected with cell types such as "CD4+ T cells", "CD8+ T cells", and "B cells".
- Cytotoxic Activity:** Nodes like "Cytotoxic activity", "Cytotoxic activity", and "Cytotoxic activity" are interconnected with cell types such as "CD8+ T cells", "NK cells", and "CD4+ T cells".
- Regulatory Activity:** Nodes like "Regulatory activity", "Regulatory activity", and "Regulatory activity" are interconnected with cell types such as "CD4+ T cells", "CD8+ T cells", and "B cells".
- Cell Populations:** Nodes like "CD4+ T cells", "CD8+ T cells", "B cells", "NK cells", and "CD4+ T cells" are interconnected with each other, forming a dense web of relationships.

The diagram highlights the intricate network of interactions that underpin the immune system's response to various stimuli, including pathogens and tissue damage.

Zhang et al (2023): A systematic evidence map of chronic inflammation and immunosuppression related to per- and polyfluoroalkyl substance (PFAS) exposure. *Environ Res.* 2023 Mar 1;220:115188. doi: 10.1016/j.envres.2022.115188. Epub 2022 Dec 30. PMID: 36592815; PMCID: PMC10044447.



Singh and Hsieh (2021): Exploring Potential Carcinogenic Activity of Per- and Polyfluorinated Alkyl Substances Utilizing High-Throughput Toxicity Screening Data. *Int J Toxicol*. 2021 Jul-Aug;40(4):355-366. doi: 10.1177/10915818211010490. Epub 2021 May 4. PMID: 33944624.

IARC classifications for PFOA and PFOS

International Agency
for Research on Cancer




World Health
Organization

Table 1. Summary of classifications in IARC Monographs Volume 135


Agent	Evidence stream			Overall evaluation
	Cancer in humans	Cancer in experimental animals	Mechanistic evidence (key characteristics of carcinogens)	
Perfluorooctanoic acid (PFOA)	Limited (renal cell carcinoma and testicular cancer)	Sufficient	Strong in exposed humans (KCs 4, 7), human primary cells (KCs 5, 7, 8), experimental systems (KCs 4, 5, 7, 8, 10)	Group 1
Perfluorooctanesulfonic acid (PFOS)	Inadequate	Limited	Strong in exposed humans (KCs 4, 7), human primary cells (KCs 5, 7, 8), experimental systems (KCs 4, 5, 7, 8, 10)	Group 2B

KCs, key characteristics of carcinogens; KC4, induces epigenetic alterations; KC5, induces oxidative stress; KC7, is immunosuppressive; KC8, modulates receptor-mediated effects; KC10, alters cell proliferation, cell death, or nutrient supply.

IARC MONOGRAPHS VOL. 135
PERFLUOROOCTANOIC ACID (PFOA) AND
PERFLUOROOCTANESULFONIC ACID (PFOS)
(7–14 NOVEMBER 2023)





PFOA



PFOS

Group 1
Carcinogenic to humans

Sufficient evidence for cancer in animals and strong mechanistic evidence in exposed humans:






Epigenetics Immunosuppression

Limited evidence for cancer in humans (for renal cell carcinoma and testicular cancer)

Group 2B
Possibly carcinogenic to humans

Strong mechanistic evidence in exposed humans:

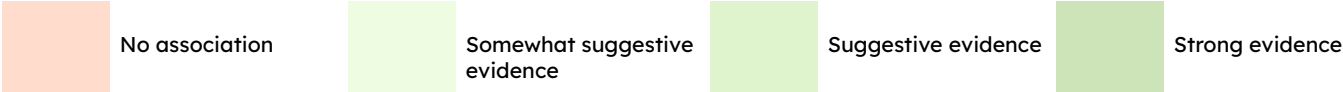



Epigenetics Immunosuppression

IARC GROUP

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2—Is genotoxic	PFOA	PFOS, PFNA, PFDA, PFHxS	PFHxA, GenX, PFBS	PFAS are not directly mutagenic; Evidence of DNA damage in some assays likely from secondary event such as oxidative damage
3—Alters DNA repair or causes genomic instability	Data gap	Data gap	Data gap	Data gap
4—Induces epigenetic alterations	PFOA	PFOS, PFHxS, PFNA, PFUnA	Data gap	Observations of differentially methylated regions and changes in global methylation in human cohorts, and <i>in vitro</i> assays
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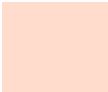
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7—Is immunosuppressive	PFOA	PFOS, PFHxS, PFNA, PFDA, PFOSA, 8:FTOH	PFBS	Reduced vaccine response in humans, decreased T cell-dependent antibody response in animals, changes in immune cell populations
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10—Alters cell proliferation, cell death or nutrient supply	PFOA	PFOS, PFHxS, PFNA, 8:2 FTOH	PFBS, PFHxA, 6:2 FTOH	Increases in proliferation, migration and invasion in cancer cell lines, cell cycle disruption,

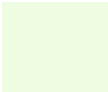


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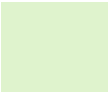
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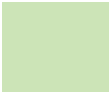
No association



Somewhat suggestive evidence



Suggestive evidence



Strong evidence

PFAS Regulatory Guidelines based on Cancer Endpoints

- Strictest drinking water standards and guidelines for PFAS are based on cancer endpoints
- EPA Proposed Maximum Contaminant Level
 - PFOA - 4 ppt, zero for MCLG
 - PFOS - 4 ppt, zero for MCLG
- California Public Health Goal
 - PFOA - 0.007 ppt
 - PFOS - 1 ppt



Addressing Data Gaps



Search

The numbers in the heat map indicate the number of studies, not the number of significant effects. Click to select studies, click again to deselect.

Colors correspond to the study type: human in green, animal in blue, in vitro in orange.

		Colors correspond to the study type: human in green, animal in blue, in vitro in orange.																			
PFAS	Total	Metabolic & Digestive System	Body Weight, Size & Growth	Endocrine System	Systemic/ Non-specific/ Other	Reproductive System	Cell Toxicity / Mortality	Circulatory System	Nervous System & Behavior	Immune System	Urinary System	Respiratory System	Musculoskeletal System	Genotoxicity	Sensory System	Cancers					
PFNA	631	11563321657	1	1294935	222940	13320	8	1264752	912	43154	46144	4193	23	189	53615	4114	1				
PFHxS	578	125243216833	1	1251937	231429	13410	3	1153551	88	39148	84981	417	213	186	27	415	116				
PFDA	506	70106368871	75	3531	95547	8814	3	174929	1411	23133	3022	520	161	116	315	7	247				
PFUnDA	297	5422196728	59	1525	10718	60	9	822	266	713	72	178	211	41	113	1	24				
PFAS mix	204	4035113931	49	2414	52210	2915	2	219	1812	141	717	29	121	7	9	5	4				
PFDoDA	203	2026182928	29	1724	51228	3214	3	823	74	79	82	124	6	4	17	2	11				
PFBS	150	1018191221	14	1328	51819	1615	2	21	253	97	418	4	5	5	2	5	1				
PFHpA	143	251417279	22	920	5717	32	4	16	20	123	4	5	3	2	8	5	2				
PFHxA	120	1214261312	10	527	1125	7	8	2	14	29	3	67	9	2	2	4	1				
PFBA	99	91322917	6	529	214	18	7	4	1	13	25	1	6	5	4	1	2				
PFTyDA	90	111371618	14	13	8	2	5	7	13	6	3	5	3	3	2	1	5				
PFTeDA	67	9712613	5	711	23	11	4	3	1	2	11	1	1	3	1	2	3				
MeFOSAA	66	15	1	20	15	1	1	19		5	10		1	8		1	3				
PFAS + other	59	1237215	4	16	10	16	4	4	10	1	9	10	2	5	2	10	2				
PFHpS	58	112119	3	15	3	2	1	1	20	1	2	5	1	5	1	1	4				
PFPeA	57	651285	6	111	13	18	6	3	4	11	1	2	2	1	1	1	3				
EtFOSAA	49	11	1	10	1	10	1		2	14		4		9		1	6				
6:2 CI-PFESA	44	610410	12	6	10	4	1	11	2	8	5		11	5	4	3	2				
GenX	29	10	9	10	8	9	9	7	6	2	10	11		5	2		4				
PFDS	24	5	5	1	6	4	2	2	2	1	1	2	1	1	1	1	1				
8:2 CI-PFESA	13	3	1	1	5	3	1	2	1	3	1	2	2	2		1	1				
6:2 FTSA	11	3	3	5	1			2	1			4	1		1		1				
HFPO-TA	6	1	1	2	1	1	2		1			1		1			1				
ADONA	5	1	1	1	1	2	2		1		1	2		1		1	1				
PFO4DA	5	1	2	1	2	1	2	1	1	1	1	1		1	1	1	1				
PFO5DoDA	5	1	3	2	1	3	3	1	1	1	2		2	1	2		1				
PFPeS	5	2	1	1	1	1	1		1		1			1			1				
Nafion BP2	2	2	1	1	1	1			1					1							
PFNS	1	1			1																

Filters

Refresh page to reset all filters

Study Type

Click for study type specific histograms, hover for study counts

human animal in vitro

Early Life Effects

Show All Effects

Financial Conflict of Interest

(All)

Selected Studies

Hover to see details, click for PubMed.

- Abe et al. 2017
- Abe et al. 2017
- Abercrombie et al. 2021
- Abraham et al. 2020
- Adinehzadeh and Reo 1998
- Adinehzadeh et al. 1999
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Download Study List

In summary:

- Multiple PFAS exhibit several key characteristics of carcinogens
- Epigenetics and immune impacts are emerging as key mechanisms for PFAS carcinogenic properties
- Data gaps remain, and there is a need to investigate and screen poorly characterized PFAS
- Regulators and risk assessors can use this approach to effectively regulate groups and classes of PFAS



- On Amphibian
- On Aquatic mammal
- On Bird
- On Fish
- On Large mammal
- On Other
- On Reptile
- On Small mammal
- On U.S. EPA fish

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Thank you

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