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Evidence mapping and scoping review of pathways for potential dietary exposure to per- and poly-fluoroalkyl substances (PFAS)†

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Concern for exposure to per- and poly-fluoroalkyl substances (PFAS) has been growing over the past couple of decades as more information is obtained and understood. PFAS are environmentally persistent and have found their way into the food chain. A better understanding of the impact to humans through the dietary route is imperative to address growing concerns and to mitigate these influences on the food supply. The goal of this study is to identify and map evidence in the peer reviewed literature of important pathways for dietary exposure to PFAS. A conceptual model of potential exposure pathways is described, evidence for these pathways from two previous systematic literature reviews is collated, and additional information on potential for PFAS transfer to food from targeted reviews is distilled. Evidence mapping confirms significant evidence for occurrence of legacy PFAS in foods and for association of dietary intake of certain foods with measured body burden for these chemicals. More limited information on sources of PFAS in agricultural inputs and food processing suggest important exposure pathways for consumers. There is also limited research reporting chemical transfers during food storage and preparation. Direct measurements for most PFAS in foods and for transfers from contaminated environmental media to foods remain limited. Addressing the most important gaps in the evidence for PFAS exposure through the dietary pathway will support actions to mitigate and prevent health impacts.

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Environmental significance

Mapping of evidence for potential dietary exposure pathways for per- and poly-fluoroalkyl substances (PFAS) provides insights on sources of food contamination and identifies gaps in knowledge. Results confirmed data on occurrence of legacy PFAS in foods and only limited information on PFAS sources and transfers across the food supply chain including those associated with agricultural inputs, food processing, storage, and preparation. Future research to address these gaps will support actions to mitigate and prevent health impacts.

1 Introduction

Per- and poly-fluoroalkyl substances (PFAS) are widely used, long lasting compounds that have been measured in people, plants, animals (particularly fish), water, air, and soil all over the world.[1–3] The benefits of these thermally and chemically stable compounds have been demonstrated in their use in items such as cleaning products, clothing, cosmetics, home materials (such as carpets and upholstery), packaging (including food packaging), paint, and fire-suppressing foams, to name a few.[4] But concern for exposure to PFAS has been growing over the past couple of decades as more information is obtained and understood about these widely used substances. PFAS are environmentally persistent, ubiquitous in drinking water, and have found their way into the food chain.[5–8] Thousands of publications have provided insights to sources, environmental occurrence, and risks of PFAS.[9–13]

Holder *et al.*[11] investigated important pathways of exposure to PFAS by reviewing, curating, and mapping evidence in the literature for measured occurrence of PFAS in exposure media. Real-world occurrence for 20 PFAS was targeted primarily in media commonly related to human exposure (outdoor and indoor air, indoor dust, drinking water, food, food packaging, articles and products, and soil). Additional evidence for determinants of exposure to PFAS from consumer products and food was reviewed by systematically mapping evidence for correlates

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of PFAS in human cohort studies.[12] The first systematic evidence mapping (SEM) yielded a database with meta-data from peer-reviewed studies and, where available, quantitative information on occurrence in environmental media, including food. In the second SEM the resulting database included correlates of exposure to PFAS, as evidenced by measured PFAS values in human biomatrices and surveys of the study participants as to their dietary and product/article usage. The information in these databases can be leveraged to conduct more detailed analyses of PFAS exposure potential to a variety of sources and pathways including food and diet.

Significant questions remain related to PFAS dietary exposure pathways. Food is unique as an exposure medium because contamination comes from both ambient and indoor sources. Sources can originate upstream, during processing, and in the home (residential). A better understanding of the most important sources of PFAS food contamination is required to address growing concerns and to mitigate these influences on the food supply.

In this study, a hybrid systematic evidence mapping approach is applied to identify important PFAS dietary sources and exposure pathways along the food chain with a primary focus on perfluoroalkyl acids. A conceptual model of potential exposure pathways is described and used to guide review and evaluation of evidence in the literature to identify important dietary exposure pathways as well as significant gaps in information. Data on PFAS occurrence in food and associations of foods with PFAS biomarker levels that were extracted in the two previously published SEMs[11,12] are collated and evaluated in greater detail. Additional targeted literature review is conducted to identify relevant information for data poor steps in the conceptual model. The goal of this hybrid SEM is to address the following questions. (1) What PFAS occur in which foods? (2) are people exposed to PFAS in the food that they consume? (3) how is food contaminated with PFAS? Results highlight important gaps in information required to support decisions that will ensure a safe and sustainable food supply free of harmful levels of PFAS.

2 Methods

2.1 Conceptual model

A conceptual model depicting the sources, transfers, and exposure pathways associated with PFAS contamination in food is presented in Fig. 1. The conceptual model was developed by considering the food supply chain starting with agricultural production, to processing, distribution, and finally consumption.[14] Potential sources of PFAS along the food supply chain were incorporated.[15] An exposure pathway for a chemical of interest includes the emission, transfer, and uptake of the chemical. Important exposure pathways may present at any stage of a chemical or product lifecycle. PFAS occurrence in food and associated PFAS dietary exposures may be the result of both direct and indirect contamination. PFAS emitted to the ambient environment from point sources (*e.g.*, industrial processes, fire suppression, landfill/incineration) and agricultural practices may be transferred to wildlife, livestock, and agricultural products. Additional contamination of food may occur during food processing operations, which may include converting raw agricultural products to primary ingredients, using ingredients to produce consumable food products, and then packaging and transporting to point of distribution. Finally, foods may be contaminated within the indoor environment during food storage, meal preparation, and food service. To characterize important exposure pathways, measurements can be made of PFAS emissions, as well as of occurrence in relevant

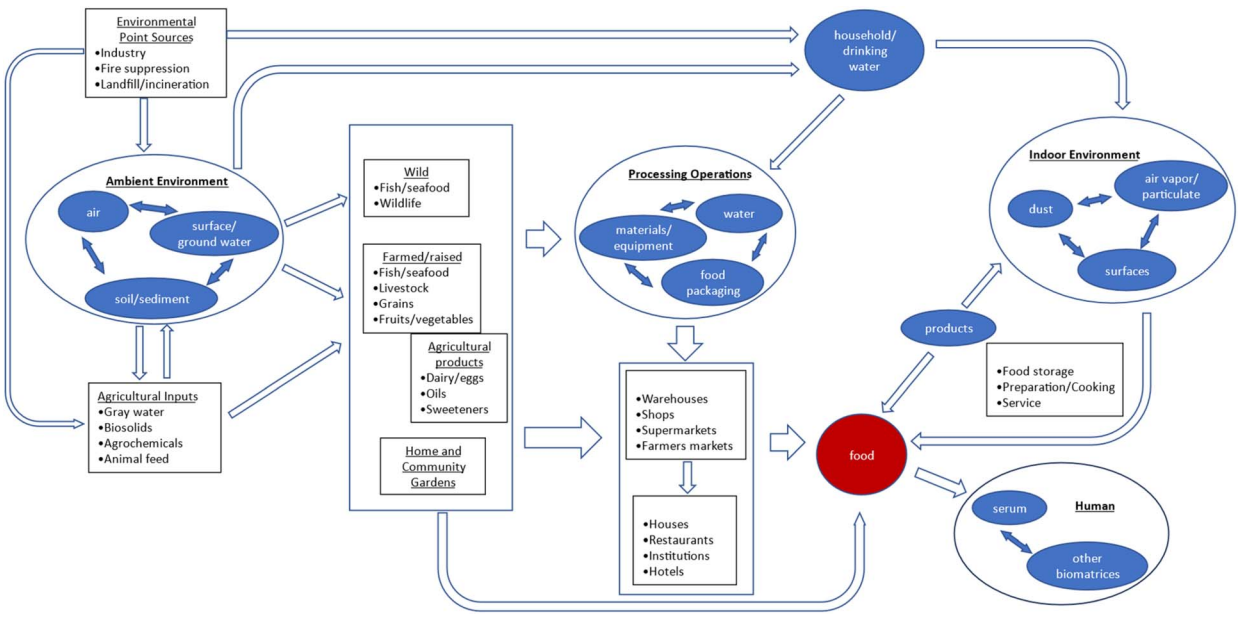


Fig. 1 Conceptual model of PFAS dietary exposure pathways; blue indicates environmental media; boxes reflect food-relevant sources; arrows indicate transfers between media and food along the food chain.

environmental and biological media. Additional exposure information to identify correlates of consumption and PFAS exposure can be developed through surveys and questionnaires of dietary behaviors and practices that are administered as part of PFAS cohort studies.

2.2 Sources of evidence

Results of two previously published literature reviews were used to provide evidence for the occurrence of PFAS in food and for PFAS dietary exposure. These two reviews focused on a subset of sixteen well-studied PFAS (ESI Table S1†). The reviews covered publications from 2003 to 2021 using Web of Science (Clarivate), PubMed (National Library of Medicine), ToxNet/ToxLine (National Library of Medicine), and ProQuest (Clarivate) databases for relevant peer-reviewed literature. Search terms and results are listed in ESI Tables S2–S8† and described in Holder *et al.*[11,12]

Holder *et al.*[11] conducted systematic evidence mapping (SEM) to identify evidence for potentially important exposure pathways. A SEM pulls together and categorizes primary research studies in a particular area, and visually distills the scope of the resulting information.[16] The authors aimed to answer the question, "for the studied communities, what media in their immediate environment are contaminated with measurable levels of PFAS?" To address this question, the authors conducted a review of peer-reviewed literature from scientific journals to identify references with occurrence data in indoor or environmental media. Detailed methods for the search strategy through the SEM, including the criteria for identifying relevant studies (*i.e.*, the Population, Exposure, Comparator, and Outcome statement [PECO statement]), are reported in Holder *et al.*[11] Detailed data were extracted on PFAS occurrence in indoor and environmental media from 229 references. Studies were most abundant for perfluorooctanoic acid (PFOA, 80% of references) and perfluorooctanesulfonate (PFOS, 77%). Many studies analyzed additional chemicals, particularly perfluorononanoic acid (PFNA) and perfluorohexanesulfonate (PFHxS) (60% of references each). Food (38%) and drinking water (23%) were the commonly studied media. Most studies found detectable levels of PFAS. The authors provided summary information on the types of food studied and frequency of PFAS detection with more detailed information extracted and published in the ESI and included here as Tables S2–S5.†

Holder *et al.*[12] applied the SEM approach to identify evidence for potential correlates of exposure, aiming to answer the question, "for the studied communities, what dietary consumptions or product/article usages are potentially correlated with levels of PFAS in human biomatrices?" The authors conducted a literature review of peer-reviewed studies with important correlates of exposure to PFAS, based on PFAS measurements in human biomatrices and survey data on dietary consumptions and product/article usage by those study participants. Detailed methods for the search strategy through the SEM, including PECO relevancy statement, are reported in Holder *et al.*[12] and in ESI Tables S6–S8.† Data were extracted and compiled on measures of PFAS correlations between biomatrix concentrations and dietary consumption and other product/article use. Studies were most abundant for dietary correlates ($n = 94$) with fewer publications reporting correlate assessments for product use ($n = 56$). Among the 94 studies of any of the 11 food categories studied (as defined in Holder *et al.*,[12] Table 2), significant correlations were reported in 83% of the studies for one or more PFAS—most commonly for seafood, meats/eggs, and cereals/grains/pulses categories. Food container and non-stick cookware categories included only 4 and 12 studies, respectively, with significant correlations reported in 2 and 8 of the studies, respectively.

In the current research, the databases created from Holder *et al.*[11,12] were used to further explore evidence related to PFAS emissions and transfers (Fig. 1) by direct mining of the databases for additional details on food-related occurrence and correlates. Evidence for elements in the conceptual model that were not addressed by Holder *et al.*[11,12] were identified for further consideration. For commonly studied PFAS, information on sources and emissions to the ambient environment has been extensively reviewed and collated (see for example in the United States the US EPA PFAS Analytics Tool).[17] Therefore, no additional review was conducted as part of this effort. However, there is currently limited information available regarding fate, transport, and transfer for PFAS and precursor compounds.[18] As such, a targeted (scoping) literature review was conducted to identify information related to PFAS transfers to foods as depicted in the conceptual model (Fig. 1). Google Scholar was used with search terms listed in Table 1 as associated with PFAS for recent studies between 2019–2023.The limited years of interest allowed for a non-systematic search that targeted specific, potentially relevant dietary sources and pathways. The targeted review searched for transfers to food through uptake from contaminated environmental media (air, water, and soil/sediment) and agricultural inputs (biosolids, compost, agrochemicals, and animal feed), as well as other transfers of PFAS to foods during food processing operations (including packaging) and from the indoor environment (including surfaces and dust, air deposition, and preparation, storage, and service). A detailed list of search results is provided in ESI Table S9.†

2.3 Evidence synthesis

The food categories presented in Holder *et al.*[11,12] were synthesized at a high level for comparison with other environmental

Table 1 Search terms used for targeted literature review with the number of relevant papers retrieved

Food plant uptake	27
Livestock/dairy/egg uptake	18
Biosolids and compost	13
Agrochemicals/fertilizers	4
Farm waste use/reuse	1
Fish/seafood/wildlife	16
U.S. total diet study	2
Packaging/processing	13
Cooking effects	3
Modeling	4

Table 2 Groupings of food items for data analysis[a]

Beverages	(1) **Alcohol**: beer, wine, spirits (2) **Other (excluding milk and water)**: coffee, tea, soda, juice, hot chocolate
Grains	Barley, rice, oat, wheat, cereal, pasta, bread, tortilla, biscuit, pancake and waffle, bagel, English muffin, roll. Allowed for corn when part of a mix of cereals
Dairy	(1) **Milk** (2) **Other**: cheese, cottage cheese, cream cheese, sour cream, butter, yogurt, ice cream, processed milk products, formulated milk beverages, combinations of milk and other dairy products. Allowed for "butter or margarine"
Fats/oils	Cooking oil, salad dressing, margarine, mayonnaise
Fruit	Berry, citrus, pome, stone. Allowed for mix of fruit and juice
Vegetables	Tomato, leafy, root and tuber, mushroom, corn, string bean. Allowed for pea when mixed with vegetables. Allowed for coleslaw and french fries. Allowed for mix of vegetable, juice, sauce
Plant-based protein foods	Bean, pea, legume, nut and nut butter, soy products including tofu
Meat and egg	(1) **Beef**: Hamburger, steak (2) **Pork**: allowed for a mix of pork and cured meats if the cured meats are pork-based (3) **Game**: deer, reindeer, moose, grouse, alligator (4) **Other Mammal**: lamb and sheep, mixed mammal meat (*e.g.*, "red meat") or unspecified mammal meat (*e.g.*, barbecue) (5) **Poultry**: chicken and nuggets, Turkey, duck (6) **Offal**: organ, blood (7) **Cured meat**: bacon, sausage, hot dog, salami, bologna (8) **Other meat**: mixed meat, unspecified meat (9) **Egg**: chicken egg, gull egg
Seafood	(1) **Freshwater fish**: catfish, carp, tilapia, bluegill, perch, pike, minnow, trout (2) **Marine fish**: halibut, monkfish, sea bass, cod, mackerel, whiting, hake, mullet, herring, tuna, swordfish, anchovy, sardine (3) **Other fish**: anadromous fish (*e.g.*, salmon), mix of freshwater and marine fish, or unclear if freshwater or marine (4) **Shellfish**: crab, shrimp, prawn (5) **Mollusk**: mussel, oyster, clam, scallop, cuttlefish, squid, octopus (6) **Marine mammal**: seal, whale (7) **Offal**: organ (8) **Plant**: algae, seagrass, seaweed, kelp (9) **Other**: unspecified seafood, mix of different kinds of seafood, biomarkers related to seafood consumption
Mixed dishes/overall diet	(1) **Pizza and fast food/takeout food** (2) **Other**: school lunch, microwave dinners, soup and stew, sandwich, mix of more than one other food category, overall macronutrient intake
Snacks/sweets	(1) **Microwaved popcorn** (2) **Other**: pastry, cake, pie, brownie, donut, cookie, muffin, candy, chocolate and candy bar, honey, sugar, non-microwaved popcorn, cracker, salty snack, chip/crisp, jam/jelly
Condiments/sauces	Spice, seasoning, table salt. Includes garlic and ginger
Supplements	Calcium, vitamin, fish oil
Infant foods	(1) **Human milk** (2) **Infant formula and food**
Food related products	(1) **Packaging**: aluminum bags/wrappers, microwave bags, microwave popcorn bags prior to cooking, ice cream tub, paper-based food contact materials (FCM), milk bottles, precooked food wrappers, snack and sandwich bag, fast food packaging (2) **Cooking/preparation**: microwave popcorn bags, cooked, paper materials for baking, baking cover, baking mold, food contact materials-Ceramic coated pan-PFOA free-overheating scenario, food contact materials-PTFE coated pan-low priced-PFOA free-overheating scenario, food contact materials-sandwich maker-normal application, food contact materials-waffle iron-normal application, roasting bags, cupcake cup (3) **Service**: fast food paper boxes and wrappers, ice cream cup, carboard cup, paper cup and plates, tableware, coffee cups, popcorn bucket

[a] Non-bold font shows examples of the food items and food related products.

media. In this study, the extracted databases were evaluated for food subcategories as identified by the National Health and Nutrition Examination Survey – What We Eat In America (NHANES WWEIA)[19] to provide more specificity and detail for analysis of potential dietary exposure. In addition, relevant products were considered. The food groupings and related products are summarized in Table 2. Study data from the Holder *et al.*[11,12] databases were used for measured PFAS occurrences and correlations between reported consumption or

usage and biomatrix levels of PFAS based on these new groupings and products.

To evaluate evidence for which PFAS occurred in which foods, the refined categories were used. Counts of studies reporting occurrence for each combination of PFAS and food group or food contact material were collated and mapped (ESI Fig. S1†). Occurrence studies are counted only where occurrence was quantified in units of concentration (rather than as a percentage of total PFAS occurrence) and only where the occurrence data represented point values or means, percentiles, or ranges (rather than standard deviations or standard errors). Some studies focused on quantification rather than detection when defining occurrences above analytical limit levels. In those cases, values above the limit of quantification/method quantification limit (where they were known) were included in the mapped counts. For some database records for some studies, it was not reasonably clear from the detection or quantification limits and occurrence values recorded in the database whether the occurrences were above or below limit levels. For those records, the full text of the study was examined to make determinations, though for a small number of records from 14 studies, a reasonable determination could not be made, and they were not included. Generally, these were records where the authors provided a level of detection as a range of values (*e.g.*, encompassing different media), and the measured occurrences fell inside that range. Occurrence values were not reported in studies included in the database for the following food groups: pizza, fast food/takeout food, microwaved popcorn, and supplements. Occurrence values for perfluorononanesulfonic acid (PFNS) and perfluoropentanesulfonic acid (PFPeS) were not reported in studies included in the database for any food groups or food contact materials; therefore, these are not discussed further.

To evaluate evidence of human exposure to PFAS in foods consumed, counts of studies reporting significant PFAS exposure correlations are mapped for each combination of PFAS and food group or food contact material (ESI Fig. S2†). For some combinations of PFAS and food group or food contact material, some studies found a mix of significant positive, significant negative, or null correlations depending on the location, subpopulation, response level, *etc*.—this level of detail (including the relatively small number of null correlations) is not captured in ESI Fig. S2† but can be found in the database and summarized in Holder *et al.*[12] and in ESI Table S10.† Only those scenarios where it was clear that authors evaluated correlates in adjusted statistical models are shown. A study was included in ESI Fig. S2† if at least one scenario (one specific food or food contact item, one specific response level, one specific subpopulation, *etc.*) had a significant positive or significant negative correlation.

As described in Holder *et al.*,[11] the search-and-extraction strategy for occurrence values focused on values recorded from locations in the US, Canada, and Europe, but if those studies also presented values observed in other countries, those values were also extracted. That is, the strategy was systematic for data observed in the US, Canada, and Europe, but not systematic for other countries. On the other hand, as described in Holder *et al.*,[12] the search-and-extraction strategy for exposure correlates was not limited by the country origin. In the correlates database from Holder *et al.*,[12] 76 of the 103 studies (74%) included information from populations in the US, Canada, or Europe or their territories. In the current study, all the data were utilized without filtering by country of origin.

To evaluate evidence for food contamination with PFAS, occurrence in food packaging was considered. In addition, the results of the scoping review addressed less studied pathways along the supply chain within the conceptual model.

3 Results

3.1 Systematic mapping of evidence for PFAS dietary exposure

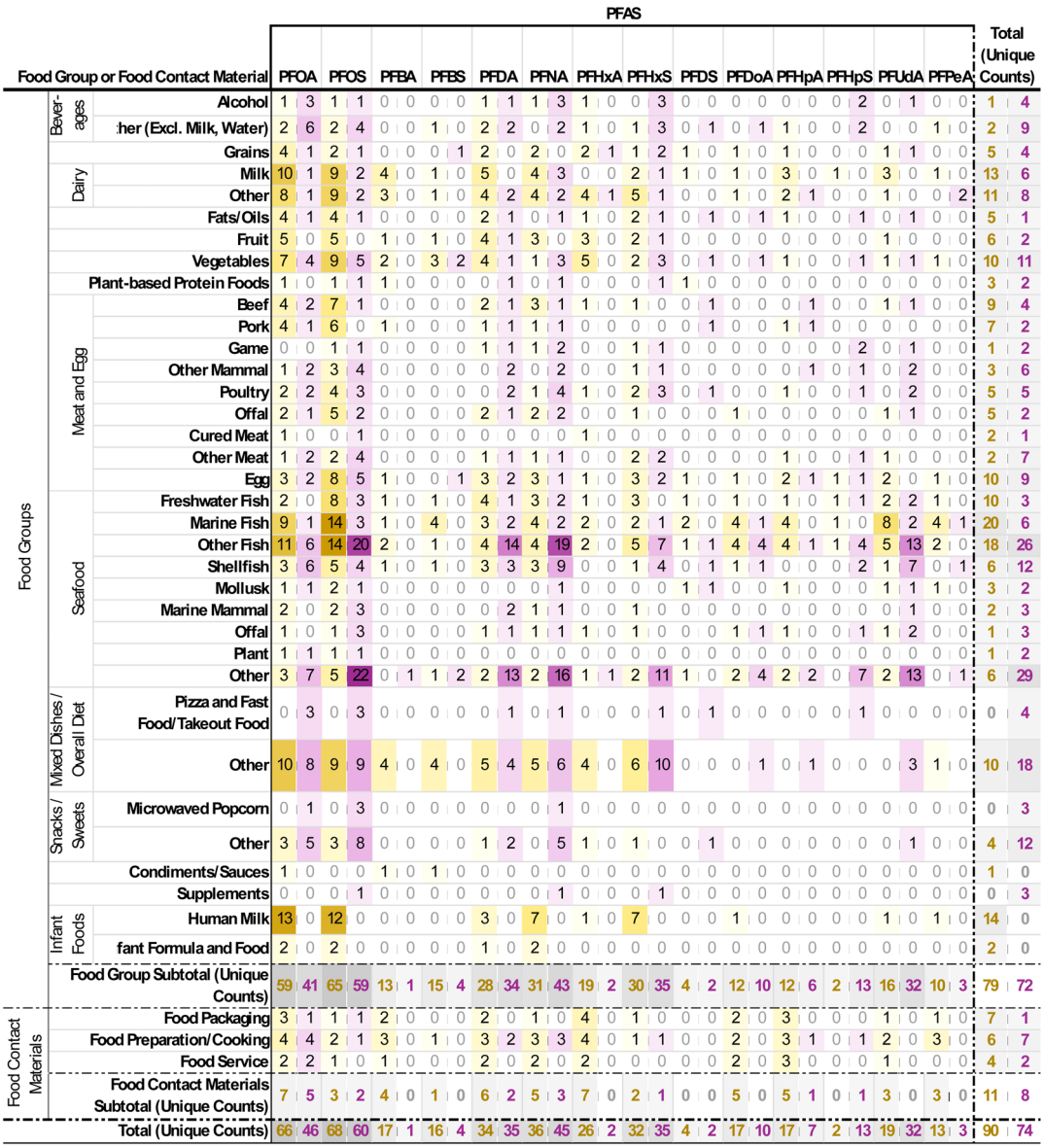
Counts of studies reporting occurrence for each combination of PFAS and food group or food contact material were collated and mapped (ESI Fig. S1†). The number of PECO-relevant studies with detectable or quantifiable PFAS occurrence values, and the number of studies in the database reporting any PFAS occurrence values are indicated, as recorded in the Holder *et al.* database.[11]

Counts of studies reporting significant PFAS exposure correlations are mapped for each combination of PFAS and food group or food contact material (ESI Fig. S2†). The number of PECO relevant studies finding significant positive correlations and significant negative correlations, as recorded in the Holder *et al.*[12] database is indicated. A positive correlation means that increasing concentrations of PFAS were observed in the biomatrix with increasing dietary consumption or use of food contact material.

Of the 35 food groups shown in ESI Fig. S2,† Holder *et al.*[12] did not investigate condiments/sauces, human milk, and infant formula and food; therefore, they are not included in the database. Correlation values for PFNS and PFPeS were not reported in studies included in the databases for any food groups or food contact materials; therefore, these are not discussed further. In ESI Table S10† a breakdown of the combinations of PFAS and food group or food contact material referenced in each study is provided, with indicators of which scenarios had significant findings with directionality indicated (*i.e.*, positive, negative, or no correlations).

Results of the two SEMs are synthesized in Fig. 2. The values shaded in orange are from ESI Fig. S1†—they are the number of PECO-relevant studies with detectable or quantifiable PFAS occurrence values, as recorded in the Holder *et al.* database.[11] The values shaded in purple are from ESI Fig. S2†—they are the numbers of PECO-relevant studies that found a significant positive correlation between biomatrix concentrations and dietary consumption or usage of food contact materials, as recorded in the Holder *et al.* database.[12]

Substantial evidence was found for occurrence of several PFAS in several food categories. Overall, detectable or quantifiable levels of one or more PFAS were found in foods in 79 studies. Detectable or quantifiable levels of PFOA or PFOS were reported in five or more studies for milk, other dairy, fruit, vegetables, beef, pork, offal, eggs, freshwater fish, marine fish,



Food Group or Food Contact Material			PFOA	PFOS	PFBA	PFBS	PFDA	PFNA	PFHxA	PFHxS	PFDS	PFDoA	PFHpA	PFHpS	PFUdA	PFPeA	Total (Unique Counts)	
Food Groups	Beverages	Alcohol	1	3	1	1	0	0	0	1	1	1	3	1	0	0	3	0	0	0	0	0	0	2	0	1	0	0	1	4
		:her (Excl. Milk, Water)	2	6	2	4	0	0	1	0	2	2	0	2	1	0	1	3	0	1	0	1	1	0	0	2	0	0	2	9
		Grains	4	1	2	1	0	0	0	1	2	0	2	0	2	1	1	2	1	0	1	0	1	0	0	0	1	1	0	0	5	4
	Dairy	Milk	10	1	9	2	4	0	1	0	5	0	4	3	0	0	2	1	1	0	1	0	3	0	1	0	3	0	1	0	13	6
		Other	8	1	9	2	3	0	1	0	4	2	4	2	4	1	5	1	0	0	1	0	2	1	0	0	1	0	0	2	11	8
		Fats/Oils	4	1	4	1	0	0	0	0	2	1	0	1	1	0	2	1	0	1	0	1	1	0	0	1	0	1	0	0	5	1
		Fruit	5	0	5	0	1	0	1	0	4	1	3	0	3	0	2	1	0	0	0	0	0	0	0	0	1	0	0	0	6	2
		Vegetables	7	4	9	5	2	0	3	2	4	1	1	3	5	0	2	3	0	1	0	1	1	0	0	1	1	1	1	0	10	11
		Plant-based Protein Foods	1	0	1	1	1	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	3	2
	Meat and Egg	Beef	4	2	7	1	0	0	0	0	2	1	3	1	1	0	1	0	0	1	0	0	0	1	0	0	1	1	0	0	9	4
		Pork	4	1	6	0	1	0	0	0	1	1	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	7	2
		Game	0	0	1	1	0	0	0	0	1	1	1	2	0	0	1	1	0	0	0	0	0	0	0	2	0	1	0	0	1	2
		Other Mammal	1	2	3	4	0	0	0	0	2	0	2	0	0	0	1	1	0	0	0	0	0	1	0	1	0	2	0	0	3	6
		Poultry	2	2	4	3	0	0	0	0	2	1	4	1	0	2	3	0	1	0	0	1	0	1	0	1	0	2	0	0	5	5
		Offal	2	1	5	2	0	0	0	0	2	1	2	2	0	0	1	0	0	0	1	0	0	0	0	0	1	1	0	0	5	2
		Cured Meat	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
		Other Meat	1	2	2	4	0	0	0	0	1	1	1	1	0	0	2	2	0	0	0	0	1	0	0	1	1	0	0	0	2	7
		Egg	3	2	8	5	1	0	0	1	3	2	3	1	1	0	3	2	1	0	1	0	2	1	1	1	2	0	1	0	10	9
	Seafood	Freshwater Fish	2	0	8	3	1	0	1	0	4	1	3	2	1	0	3	0	1	0	1	0	1	0	1	1	2	2	1	0	10	3
		Marine Fish	9	1	14	3	1	0	4	0	3	2	4	2	2	0	2	1	2	0	4	1	4	0	1	0	8	2	4	1	20	6
		Other Fish	11	6	14	20	2	0	1	0	4	14	4	19	2	0	5	7	1	1	4	4	4	1	1	4	5	13	2	0	18	26
		Shellfish	3	6	5	4	1	0	1	0	3	3	3	9	0	0	1	4	0	1	1	1	0	0	0	2	1	7	0	1	6	12
		Mollusk	1	1	2	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	1	1	1	0	3	2
		Marine Mammal	2	0	2	3	0	0	0	0	2	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3
		Offal	1	0	1	3	0	0	0	0	1	1	1	1	1	0	1	0	0	0	1	1	1	0	0	1	1	2	0	0	1	3
		Plant	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
		Other	3	7	5	22	0	1	1	2	2	13	2	16	1	1	2	11	1	0	2	4	2	2	0	7	2	13	0	1	6	29
	Mixed Dishes / Overall Diet	Pizza and Fast Food/Takeout Food	0	3	0	3	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	4
		Other	10	8	9	9	4	0	4	0	5	4	5	6	4	0	6	10	0	0	0	1	0	1	0	0	0	3	1	0	10	18
	Snacks / Sweets	Microwaved Popcorn	0	1	0	3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
		Other	3	5	3	8	0	0	0	0	1	2	0	5	1	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	4	12
		Condiments/Sauces	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		Supplements	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	Infant Foods	Human Milk	13	0	12	0	0	0	0	0	3	0	7	0	1	0	7	0	0	0	1	0	0	0	0	0	1	0	1	0	14	0
		fant Formula and Food	2	0	2	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
		Food Group Subtotal (Unique Counts)	59	41	65	59	13	1	15	4	28	34	31	43	19	2	30	35	4	2	12	10	12	6	2	13	16	32	10	3	79	72
Food Contact Materials		Food Packaging	3	1	1	1	2	0	0	0	2	0	1	0	4	0	1	0	0	0	2	0	3	0	0	0	1	0	1	0	7	1
		Food Preparation/Cooking	4	4	2	1	3	0	1	0	3	2	3	3	4	0	1	1	0	0	2	0	3	1	0	1	2	0	3	0	6	7
		Food Service	2	2	1	0	1	0	0	0	2	0	2	0	2	0	0	0	0	0	2	0	3	0	0	0	1	0	0	0	4	2
		Food Contact Materials Subtotal (Unique Counts)	7	5	3	2	4	0	1	0	6	2	5	3	7	0	2	1	0	0	5	0	5	1	0	1	3	0	3	0	11	8
		Total (Unique Counts)	66	46	68	60	17	1	16	4	34	35	36	45	26	2	32	35	4	2	17	10	17	7	2	13	19	32	13	3	90	74

Notes: PFAS = per- and poly-fluoroalkyl substances; Excl. = excluding; see Supplemental Table S1 for full chemical names. The value shading corresponds to the magnitudes of the study counts: gray spectrum for totals across PFAS and totals across food groups/food contact materials (no shading applied to the total-subtotals or total-totals on the far right); orange spectrum for individual scenarios of occurrence; purple spectrum for individual scenarios of correlation. Totals use orange font for occurrences and purple font for correlations (no color gradients). Counts of 0 use gray font.

Fig. 2 Left column: counts of PECO-relevant studies with detectable or quantifiable occurrence values (as extracted into the PFAS occurrence database in Holder *et al.*, 2023); right column: counts of PECO-relevant studies reporting significant positive correlations between biomatrix concentrations and dietary consumption or usage of food contact materials (as extracted into the PFAS exposure correlates database in Holder *et al.*, 2024). Notes: PFAS = per- and poly-fluoroalkyl substances; Excl. = excluding; see ESI Table S1† for full chemical names. The value shading corresponds to the magnitudes of the study counts: gray spectrum for totals across PFAS and totals across food groups/food contact materials (no shading applied to the total-subtotals or total-totals on the far right); orange spectrum for individual scenarios of occurrence; purple spectrum for individual scenarios of correlation. Totals use orange font for occurrences and purple font for correlations (no color gradients). Counts of 0 use gray font.

other fish, shellfish, other seafood, other mixed dishes/overall diet, and human milk. PFNA, perfluorodecanoic acid (PFDA), and perfluoroundecanoic acid (PFUdA) occurrences above detection or quantification levels were reported less frequently, most commonly associated with milk, seafoods, other mixed dishes/overall diet (PFNA and PFDA only), and human milk (primarily PFNA). Occurrences of other PFAS were reported less frequently across food categories due either to lack of

measurable levels or because these PFAS were included as analytes less frequently. PFAS occurrence was detected or quantified in food contact materials in a total of 11 studies (7 studies for food packaging, 6 studies for food preparation/cooking materials, and 4 studies for food service materials), particularly for PFOA and perfluorohexanoic acid (PFHxA) (7 studies each) and PFDA (6 studies), while perfluorodecanesulfonic acid (PFDS) was not detected/quantified and perfluorobutane sulfonate (PFBS) was detected/quantified in only 1 study.

Overall, 74 unique studies were reported with significant positive PFAS/food category combinations associated with biomatrix levels. Across all food categories, PFOA and PFOS had 41 and 59 positive associations, respectively. Several other PFAS also had greater than 30 positive associations including PFNA, PFDA, PFUdA, and PFHxS. Higher positive/negative correlation ratios (ratio of number of studies reporting significant positive correlations to the number reporting significant negative correlations) were most commonly found for some categories of beverages, meats, eggs, seafood, snacks/sweets and supplements (ESI Fig. S2†). High negative/positive correlation ratios were found for grains, fats/oils, and plant-based protein foods (ESI Fig. S2†). Significant positive correlations were reported for several PFAS in the food preparation/cooking material category.

Overall, the PFAS dietary occurrence and correlates results extracted from the literature provide substantial evidence for the importance of the dietary pathway for human exposure. PFOA and PFOS occurrences were reported most often and one or both were measured at detectable or quantifiable levels in at least five studies for 15 of 35 food categories, and in at least one study in 32 of 35 food categories. PFHxA, PFNA, PFDA, and PFHxS were also all reported at detectable or quantifiable levels in 13 food categories. Occurrence of shorter-chain PFAS, including perfluorobutanoic acid (PFBA), PFBS, and perfluoropentanoic acid (PFPeA) were reported less frequently, in part because fewer studies included these as target analytes. PFOA, PFOS, PFNA, PFDA, PFUdA, and PFHxS in food had significant positive correlations with biomatrix levels in 30 or more studies. Significant positive correlations were observed for 32 of the 35 food categories in at least one study, with one or more seafood category and other mixed dishes/overall diet having the greatest number of studies reporting significant positive correlations.

The identification of food groups that positively correlate with PFAS biomarker measurements can be further studied to determine potential sources of contamination. The focus is on the positive correlations as they imply raised levels of PFAS in both the food and biomarker measures. The food categories with significant positive correlations for more than 10 studies includes vegetables, shellfish, other fish, other seafood, other mixed dishes/overall diet, and other snacks/sweets. Among all food categories, two seafood categories had the largest numbers of studies finding significant positive correlations: 26 studies for other fish and 29 studies for other seafood. Seafood stands out as an important source of PFAS exposure. Mixed dishes, excluding pizza or fast food/takeout, are another source of probable PFAS exposure, though that same food category had a similar number of studies with significant negative correlations.

3.2 Evidence for pathways of food contamination from targeted review

Further evidence of PFAS dietary exposure pathways is provided by results of the targeted literature review focused on mechanisms for PFAS contamination of foods including transfers between media (Fig. 1). Industrial releases of PFAS into the ambient environment are being curated and reviewed by others (see for example PFAS Analytics Tools).[17] Therefore, the scope of this review and the associated results is emissions and transfers that are less well studied.

3.2.1 Ambient environment. Agricultural Inputs (gray water, biosolids, agrochemicals, animal feed): Application of biosolids to land can lead to PFAS contaminants in the soil, groundwater, and plants.[20–22] Compost has also been shown to contain PFAS, so its use as a fertilizer or soil amendment may result in PFAS transfer to soil then any plants growing in it.[23] This limited information provides evidence of potential contamination during transfers to intermediate steps on the route of exposure.

Fish and wildlife: PFAS in the environment and waterways has worked its way into freshwater and marine fish. Consumption of fish has been identified as a primary source of PFAS exposure. Several publications have measured PFAS in fish, both whole and tissue, and found PFOS as the prominent contaminant.[24–30] PFOS has been voluntarily phased out of production beginning in 2000, yet it persists in fish decades later. With fish not only being consumed by humans but also wildlife, risks may be significant to both.

Livestock, eggs, dairy: PFOS concentrates in liver, kidneys, plasma, and, to a lesser extent, muscles. Domesticated animals seem to follow the same series of impacts to organs. As outlined in the review paper by Death *et al.*,[31] livestock may be exposed through contaminated water, soil, air, or feed. An integrated crop-livestock system is in play to where PFAS contamination in the environment gets transferred to livestock then to products such as dairy.[32] Mikkonen *et al.*[33] found that cattle meat from cows grazing on PFAS contaminated sites might contain PFOS levels that exceed European Commission Maximum Limits health guidelines. A seasonal component may play a role in the potential exposure to PFAS resulting in possible errors if only steady state conditions are considered.[33] Milk samples across the U.S. from regions of concern based on biosolids usage and proximity to fire training sites were below detectable levels for 27 types of PFAS; therefore, this was considered to be a low risk of exposure.[34] Several PFAS transfer to egg yolk. Gockener *et al.*,[35] demonstrated a connection between contaminated feed and concentrations in egg yolks. The levels decreased after the source of PFAS was removed and reached non-detectable levels by 28 days.

Plant uptake: PFAS have been detected in plants. Sources of PFAS in plants can be industrial discharge, pesticide usage, irrigation, and contaminated soils from addition of compost, biosolids, or air deposition. Literature analysis shows that

a direct connection exists between PFAS in soil and bioaccumulation in plants, where the primary source is through irrigation by contaminated water.[36] The extent of the contamination is dependent on plant type, part of the plant affected, specific PFAS, and chain length. Plant uptake occurs *via* the root system and transfers to other parts, including edible fruits, vegetables, and leaves.[3] Groundwater contaminated with PFAS used to irrigate lawns or gardens may provide a source of untreated PFAS that can be transferred to vegetables. Various plant parts retain differing amounts of PFAS, but it has been shown that florets contained high levels.[37] Short-chained perfluoroalkyl carboxylic acids (<C9) tend to accumulate in the vegetable.[38]

3.2.2 Processing operations

3.2.2.1 Packaging. Food packaging includes materials that may come into contact with the food item. Materials used to create the packaging may contain chemicals such as phthalates, PFAS, brominated flame retardants, phenols, or heavy metals. These chemicals can be added to improve the functionality of the packaging. Transfer of the chemicals to the food item may occur. Several publications address the transfer of various chemicals to foods.[12] For PFAS, several individual substances can be found in food packaging and transfer to food is dependent on initial concentration and class of the substance. Heating in concert with emulsifiers or food stimulants can increase the transfer of PFAS.[39] Schaider *et al.*[40] looked at only fluorine content of commonly used food packaging, such as, dessert/bread wrappers, sandwich/burger wrappers, paperboard, and paper cups. It was found that 46% of food packaging and 20% of paperboard contained fluorine at detectable levels. This demonstrated the potential for significant contribution to dietary exposure through indirect contamination of foods.

3.2.2.2 Cooking. Bhavsar *et al.*[41] demonstrated that cooking fish does not reduce PFAS exposure regardless of the cooking technique used. Broiling, frying, or baking did not significantly change the PFAS concentrations in fish. However, a systematic review of the impact of various cooking techniques, in which Bhavsar *et al.*[41] was referenced, suggests that thermal processing does reduce PFAS concentrations in seafood and freshwater fish when cooking time is longer and liquid/animal tissue ratio

Table 3 Summary of availability of evidence: H-high; M-medium; L-low; "-" – not applicable

Dietary Exposure Pathways	Occurrence (obj. 1)	Correlates (obj. 2)	Transfers (obj. 3)
Ambient environment			
Air	L	—	—
Water	H	H	—
Soil	H	—	—
Ambient environment to foods			
Agricultural inputs	M	—	—
Fish and wildlife uptake	H	—	M
Livestock, eggs, dairy uptake	M	—	M
Plant uptake	M	—	M
Processing operations			
Materials/equipment	L	—	L
Water	L	—	L
Packaging	M	—	M
Indoor environment			
Air	L	—	L
Dust	M	—	L
Surfaces	L	—	L
Indoor environment to foods			
Products	M	—	L
Food contact materials			
Packaging	M	L	M
Preparation/Cooking	M	M	L
Service	L	L	—
Foods			
Categorized Food			
Seafood	H	H	—
Dairy	H	M	—
Others	L	L	—
Exposure route			
Biological media	—	M	—

is increased.[42] This is important because fish have been shown to be the primary food source of PFAS exposure.[43]

3.2.3 Indoor environment. The literature demonstrates a lack of information on transfers of PFAS from sources in the home environment to foods during storage, preparation, cooking, and consumption. However, extensive work has been completed on pesticide transfers from household surfaces to various food types.[44,45] If PFAS behave similarly to organic pesticides, depending on the type of food, they can transfer to an item prior to consumption. This may be especially influential when children under the age of 2 years are impacted due to their activities during consumption, *e.g.*, dropping food on floors, carrying food around the home, *etc.* prior to eating.

3.3 Evidence availability

The evidence of dietary exposure pathways to PFAS as presented in the conceptual model that has been gleaned from the literature is summarized in Table 3. Based on SEMs, substantial evidence from the literature shows that some PFAS have been widely found to occur in several types of foods (research question 1), and further evidence shows significant correlations between food consumption and levels of several PFAS in human biomatrices (research question 2). In addition, evidence of PFAS in various environments that may impact foods has been shown. For some PFAS, pathways of potential exposure have been examined and indicate that PFAS can enter food systems at several points (research question 3). However, there is very limited information regarding direct measurements of PFAS transfer from food production processes to end of life. A subjective determination of availability was graded by considering the number of papers in each category. The fewer the papers, the lower the grade.

4 Discussion

The uniquely summarized evidence mapping to a subset of PFAS demonstrates potential pathways of dietary exposures. PFAS have been widely found in foods, with 12 of 14 PFAS observed in one or more food categories in 10 or more studies. PFOA and PFOS are most commonly reported across multiple food categories and in a majority of studies. Where lower rates of detection in foods are observed (for example perfluoroheptanesulfonic acid [PFHpS] and PFDS), this may indicate their decreased usage, lack of inclusion in studies, or limitations in ability to find applicable analytical methods. The decreased discovery of these PFAS is more a reflection of the state of the research than a statement of importance to exposure assessments.

The literature searches, both systematic and targeted, revealed that some specific foods (seafood, meat, mixed dishes, milk, vegetables) are more likely than others to be susceptible to PFAS contamination. These foods could be contaminated through pathways from the ambient environment, during processing, or from the indoor environment. In addition, several PFAS (most frequently PFOA and PFOS) have been measured in human milk, representing a potentially important source of exposure for infants. The bulk of the direct evidence from the literature revealed that food may be impacted, but more limited indirect evidence indicated potential links to specific sources.

The gaps in the research are varied with respect to potential dietary exposure. Additional research on sources and pathways of PFAS in and through agricultural inputs would provide improved understanding of potential for food contamination and mitigation approaches. Only limited information is available regarding presence or absence of PFAS sources and food contamination in food processing. Additional information is required to understand if PFAS are introduced as additives, formed as impurities or residuals, or generated through transformation processes. Residential samples and assessments of transfers between indoor environmental media and foods would greatly enhance our understanding of the sources of exposure within a home environment. An understanding of the transfers between home surfaces, dust, and food are completely lacking in the literature and would significantly impact the science with respect to assessments of PFAS exposure. Because analytical methods are advancing, evidence of important dietary pathways could increase. The conceptual model provides a roadmap that researchers may find useful in filling gaps with appropriate studies.

There are limitations to the analysis. The literature reviews are necessarily time limited. As new information is published, the search strategy can be extended and implemented to support living evidence review in this rapidly advancing area. The reviews also did not consider literature from all geographic regions. Studies from other countries that were not included in the occurrence values may have provided some sources of PFAS dietary exposure such as from imported foods. The focus was on the most studied PFAS. Changes in the manufacturing and use of PFAS may result in different exposure sources and pathways. Limitations of SEM include decisions made in conducting the systematic review. Selection of search terms and inclusion criteria could influence identification of relevant studies.

In additon, each study has its own inherent limitations, *e.g.*, study design, detection limits, PFAS measured, and so on. Finally, mechanisms that influence exposure are understudied or missing from the literature, *e.g.*, transfers from surfaces to foods. As a result, understanding of the most important sources and pathways for PFAS dietary exposure remains limited. The impact is compounded when total exposure or relative source contribution information is needed in the risk assessment process.

In general, the number of PFAS assessed in the food supply has been limited primarily to several legacy chemicals and would benefit from expansion to include more emerging and precursor chemicals currently used in industrial processes and in products. The list of substances keeps growing; however, the ability to measure them has been limited. With the increasing capabilities of laboratories to identify various PFAS, especially with non-targeted analyses, more can be determined regarding the available substances within the system. However, analyses have not kept up with the expanding field of PFAS, especially for food analysis.

Insufficiency of data for multiple parts of the pathways hampers the quality of an assessment, especially for transfers, products, food packaging, and actual food items studied. However, the evidence clearly demonstrates the potential dietary exposures that exist and may be long-lasting. This is most evident with PFOS as production was reduced decades ago.

Dietary exposure to PFAS is a complicated web from sources to consumption. Taking a holistic approach by considering all pathways may be difficult but necessary to enable a complete picture of potential exposures. Foods are contaminated directly and indirectly and may be a major contributor to exposure and human health risks. The evidence shows that the dietary pathway matters for PFAS exposure. A better understanding of agricultural, processing, and residential contamination would assist in identifying the most important places where actions can be taken to mitigate potential for exposures to PFAS from food.

Data availability

This manuscript was prepared using publicly available data.

Author contribution

Lisa Jo Melnyk: funding acquisition, project administration, resources, writing – original draft, writing – review & editing. Chris Holder: data curation, formal analysis, methodology, supervision, validation, writing – original draft, writing – review & editing, visualization. Jeanne Luh: data curation, methodology, project administration, supervision, validation, writing – original draft, writing – review & editing. Kent Thomas: conceptualization, project administration, writing – original draft, writing – review & editing. Elaine A. Cohen Hubal: conceptualization, funding acquisition, project administration, writing – original draft, writing – review & editing.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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