Developing a portable method for screening PFAS in consumer products

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ENVIRONMENTAL & OCCUPATIONAL HEALTH SCIENCES
UNIVERSITY of WASHINGTON | SCHOOL OF PUBLIC HEALTH

Developing a portable method for screening PFAS in consumer products

Diana Ceballos[1], Cynthia Wu[1], Bai Li[2], Shirlee Tan[2], Aaron Specht[4], Dawn Johnston[1,3], Maria Tchong-French[1], Sonya Jampel[2,5], Trevor Peckham[3]

[1] Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, Washington
[2] Environmental Health Services Division, Public Health – Seattle & King County, Seattle, Washington
[3] Hazardous Waste Management Program in King County, Department of Natural Resources and Parks, Seattle, Washington
[4] School of Health Sciences, Purdue University, West Lafayette, Indiana
[5] Council for State and Territorial Epidemiologists, Atlanta, Georgia

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· Environmental Health Laboratory and Trace Organics Analysis Center, University of Washington, Seattle, Washington
· Eurofins Environment Testing Northern California, LLC, Sacramento, California
· Forever Analytical, South Bend, Indiana
· Washington State Department of Health, Olympia, Washington
· King County Department of Natural Resources and Parks—Parks, Water and Land Resources, Wastewater Treatment, and Solid Waste Divisions
· Department of Toxic Substances Control, California Environmental Protection Agency, Berkley, California
· Middlebury College, Middlebury, Vermont

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Executive summary

What we did

This legislative proviso project directed the University of Washington to develop and evaluate a rapid, portable, and cost-effective method to screen consumer products for PFAS (per- and poly-fluoroalkyl substances), also known as "forever chemicals," a class of environmentally persistent chemicals that have been associated with a wide range of adverse health effects. Work was conducted through collaboration with Public Health – Seattle & King County and the Hazardous Waste Management Program in King County. We assessed the suitability of a new, handheld XRF system for rapidly identifying consumer products with high fluorine content without the need to destroy them, as a proxy for identifying likely PFAS-containing items.

Why we did it

Due to growing concerns about the health effects of PFAS, particularly in children and other sensitive groups, Washington began restricting the chemicals in a number of products through its Safer Products for Washington and other forward-thinking legislation aimed at protecting public health. **Importantly, the current lack of disclosure or labeling requirements makes it difficult to know which products contain PFAS, even those marketed as "safe" or "PFAS-free."**

Standard methods for identifying PFAS content in products must be performed in a laboratory and are, therefore, costly and time-intensive. Most methods also require destroying the samples, further limiting their usefulness for frontline applications such as testing products at community events or in-home investigations. **Therefore, a quick and inexpensive screening tool is needed to identify PFAS exposure risks, allowing consumers to make informed purchasing decisions and enabling policy makers and regulators to prioritize actions.**

How we did it

We first conducted community engagement to understand better products of concern to communities in King County, WA. Then, we prioritized five product categories for testing: children's, cosmetics and personal care, household, clothing and apparel, and containers and packaging products. We then developed a method to improve the detection of fluorine using handheld XRF and tested 92 products, selected based on community input, existing information on PFAS content, and feasibility. Results from the handheld XRF were compared with two additional gold-standard methods of measuring fluorine to assess accuracy. We also tested for 40 specific PFAS compounds to understand better which chemicals are most commonly found in the everyday products we tested.

What we found

This project evaluated the performance of handheld XRF for detecting total fluorine as a proxy for PFAS in consumer products. Our findings show:

- **Handheld XRF reliably detected fluorine in products with high fluorine levels (>450 parts per million) confirmed by lab testing.** Further refinements are necessary to enhance detection at lower levels and minimize the risk of false positives or negatives.
- **The three tested fluorine methods were in relatively good agreement,** with 61% of products testing negative for fluorine across all methods and 11% testing positive by each approach. Method differences may be due to variations in how fluorine is measured and how the sample material affects those measurements.
- **Many of the products prioritized through community engagement contained high levels of fluorine,** including children's clothing, cosmetics, nonstick pans, and outdoor clothing.

Limitations and opportunities for refinement

While handheld XRF was shown to be effective for detecting high fluorine concentrations, **further refinement is needed to improve XRF performance at low-to-moderate fluorine levels.** Method improvements—such as better calibrations to account for variation in product composition, developing a protocol for complex sample types (e.g., powders, gels), and enhancing usability (e.g., incorporating software with automatic quantification)—will increase accuracy and confidence in field applications.

Potential applications and next steps

Based on study results, the handheld XRF can support:

- **Consumer education:** Enabling rapid on-site screening and raising awareness of potential PFAS exposures in everyday products, such as at community product testing events.
- **Regulatory support:** Prioritizing products for regulatory action and ground truthing the effectiveness of existing restrictions on PFAS.
- **Product replacement programs:** Help identify PFAS-containing products that should be prioritized for replacement.
- **Sustainable purchasing guidance:** Helping institutions guide purchasing decisions and identify products that should be avoided or may require further information from vendors.

To build on this work, we recommend:

- **More testing** on additional product categories of concern.
- **Improving field protocols** and methods to test non-solid products (e.g., gels, powders).
- **Tailoring XRF calibrations** for a wider range of materials.
- **Deploying the handheld XRF** to support community-based product screening events.

Conclusion

The optimzed handheld XRF may serve as a first-line screening tool to identify products likely to contain high PFAS levels. This new method offers a promising, non-destructive, portable method for rapidly screening consumer products for PFAS by semi-quantitatively measuring total fluorine. While not a definitive test for PFAS at the time of this report, it provides actionable data on total fluorine. With further refinement, handheld XRF technology can help consumers, communities, and regulators take action to reduce PFAS exposure and support safer product choices.

Introduction

Objectives

The University of Washington (UW), with support from two King County teams, Public Health – Seattle & King County (Public Health) and the Hazardous Waste Management Program in King County (Hazardous Waste), developed an optimized method for rapid detection of fluorine, a key element of all PFAS. This new method uses handheld X-ray fluorescence (XRF) technology to identify when items contain PFAS using total fluorine as a proxy. This project, funded through a proviso from the Washington State Legislature, includes:

Phase 1 – Community engagement: Conducting community engagement and a poll to understand products of concern to diverse communities and nonprofits in King County, Washington.

Phase 2 – Fluorine XRF optimization: Developing standard operating procedures for the new technology and optimizing the method for fluorine measurement.

Phase 3 – PFAS testing of consumer products: Testing the efficacy of the new technology compared to three other methods that are considered the gold standards for measuring PFAS in a sample of consumer products. Two methods measured fluorine as a tracer of PFAS (particle-induced gamma-ray emission (PIGE) spectroscopy and combustion ion chromatography) and one method measured 40 specific PFAS by liquid chromatography/tandem mass spectrometry (LC/MS-MS).

Background

PFAS in consumer products

Per- and poly-fluoroalkyl substances, or PFAS, are a group of environmentally persistent chemicals used in a wide range of consumer products. Their physicochemical properties, such as thermal and chemical stability, non-degradable nature, and ability to repel water and oils, make them useful as intentional additives in various chemical and manufacturing industries.

More than 15,000 PFAS have been identified by the U.S. Environmental Protection Agency (EPA) and over 1,400 individual PFAS are estimated to be in use globally (Gluge et al. 2020; George and Birnbaum 2024). Because these chemicals are used in so many products and processes, they are ubiquitous in our world, including in many of the products we use in our homes and businesses. Human exposure to PFAS is widespread and associated with many adverse health impacts (EPA 2025a).

There is mounting evidence that PFAS in consumer products, including children's products, contributes to human exposure (Dewapriya et al. 2023). However, it is difficult to know which products contain PFAS because disclosure by manufacturers of the chemicals used in their products is not required, nor is product labelling regarding the presence of PFAS. Thus, it is hard for U.S. consumers to know which products contain PFAS and for experts and health agencies to provide guidance on how to avoid them.

Likewise, government agencies conducting pollution prevention activities, purchasing products, or developing chemical policies are uncertain which products will release fewer PFAS into the environment or reduce human exposure. It is also difficult for local businesses to know which components of the manufacturing chain are a PFAS risk for employees and their product line. These gaps underscore the need for a quick and mobile screening method to identify possible PFAS content and prioritize safer replacements.

Therefore, understanding PFAS content in consumer products will provide the state with valuable information to help prevent exposures from products used by Washington residents. This knowledge could also help reduce sources of PFAS that we wash down the drain, send to the landfill, and release into the environment.

Health impacts of PFAS exposure

People are mainly exposed to PFAS by consuming contaminated water or food and breathing in and ingestion of indoor dust contaminated by household building materials, furnishings, and consumer products containing PFAS (ATSDR 2025). Individuals are most sensitive to exposures during certain life stages, such as childhood, pregnancy, and late in life. In addition, there is evidence that specific groups are more highly exposed due to social and economic factors that impact, for example, drinking water quality, food consumption,

occupation, or the products they use (Chang et al. 2021; Liddie et al. 2023; Li et al. 2025; Maruzzo et al. 2025)

The mechanisms by which PFAS affect the human body are complex and not yet fully elucidated (EPA 2025a,b). Still, researchers have found strong associations with various cancers, obesity, developmental diseases (e.g., low birth weight, behavioral changes), diabetes, high cholesterol, endocrine disruption, reduced immune response (including to vaccines), and reproductive health abnormalities (Fenton et al., 2021; Panieri et al. 2022; Zahm et al. 2024). Some of the PFAS-associated health risks are particularly significant in children (Ames et al. 2025) and in children of color (Chang et al. 2021).

PFAS regulations and need for testing

PFAS have been present in the environment for the last 80 years, and they will likely persist for thousands of years into the future due to their lasting nature and previously unregulated release. Although the U.S. EPA recently developed maximum contaminant levels for five PFAS in drinking water, including perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorononanoic acid (PFNA), perfluorohexane sulfonic acid (PFHxS), and hexafluoropropylene oxide dimer acid (HFPO-DA), which is also known as GenX, the agency now intends to rescind regulations associated with PFNA, PFHxS, and HFPO-DA, and no formalized federal regulations limit PFAS in consumer and industrial products (EPA 2025c).

Since 2009, the use of a particularly concerning PFAS, perfluorooctane sulfonic acid (PFOS) and its derivatives, has been restricted in Europe (ECHA 2025). The European Union has also proposed restrictions on several other PFAS (ECHA 2025). The U.S. has phased out PFOA and PFOS (EPA 2025c-e). More recently, several states in the U.S. have opted to ban the use of PFAS in a growing list of consumer products (Safer States 2025; Source Intelligence 2025; California Legislature 2025; Minneapolis Legislature 2025). The first restrictions passed in the U.S. focused on products such as firefighting foams and food packaging; however, more recent bans have extended to children's products, textiles, plastics, cleaning products, and personal care products (Safer States 2025).

In Washington in particular, Safer Products for Washington (SPWA) and other forward-thinking legislation (Washington Department of Ecology 2025a) have begun restricting PFAS in a number of product categories with known PFAS uses. However, advancing additional legislation to protect human and environmental health will require a clearer understanding of which products have high concentrations of PFAS. Until manufacturers begin regularly disclosing PFAS, we must find convenient ways to identify where the biggest exposure risks may exist so that the policy actions can be prioritized.

In Washington state, PFAS are defined as a class of chemicals that contain at least one fully fluorinated carbon atom. The carbon-fluorine bonds that characterize PFAS are among the strongest in chemistry, making them extremely persistent in the environment and earning them the nickname "forever chemicals." Many of these compounds—often those adopted

as substitutes by industry—have not been proven safe, and an increasing number are the focus of emerging health studies (Washington State Legislature. 2025a,b). A health-protective approach would be to require that lesser-studied PFAS without publicly accessible data be proven to be safe before allowing use of these forever chemicals. Replacing certain PFAS with other poorly studied PFAS is thus considered inadequate, as this practice often leads to "regrettable substitutions"—a scenario in which one hazard is removed only to introduce another.

Existing analytical methods cannot identify all individual PFAS used by manufacturers (Nordic Co-Operation 2025) and are able to detect only about 70 of the 1,000-plus PFAS thought to be in commercial use. Therefore, a quick and inexpensive screening tool is needed to identify if currently sold consumer products—including potential safer alternatives— contain any PFAS, including structures that are not identifiable through existing analytical methods. Although fluorinated minerals can be present in products such as toothpastes, supplements, and fertilizers, to name a few, PFAS are a major and most concerning source of fluorine in products (Dewapriya et a. 2023). And since all PFAS contain fluorine and its use is so ubiquitous, measurement of total fluorine is one way to flag products highly likely to contain PFAS.

The development of a portable technique to screen products for PFAS, as described in this report, will provide residents with critical information to reduce their exposure. It will also assist regulators in phasing out PFAS in products and industrial processes—such as the use of PFAS in chrome plating and extrusions of certain materials—developing replacement strategies and prioritizing future legislative actions. In addition, it will help government agencies develop messaging and strategies that support these efforts.

Methods to measure PFAS in consumer products

There are a limited number of methods for determining PFAS content in products. Some methods measure total fluorine content as a proxy for PFAS, while others measure specific types of PFAS within a sample. When possible, information on total fluorine content together with specific PFAS content within a sample provides the clearest picture.

Fluorine can serve as a useful proxy for PFAS in consumer products. In these contexts, detection of elemental fluorine generally indicates the presence of organofluorine compounds consistent with PFAS. While it is possible that inorganic fluorine—such as naturally occurring fluorinated minerals, or fluoride additives in cleaners, surface treatments, or dental products—can be present in some materials such as ceramics, glass, or toothpaste, such sources are assumed to be negligible in most consumer products. As a result, total fluorine measurements are widely accepted as an indicator of the presence of PFAS in products (Ritter et al. 2017; Schaider et al.2017; Whitehead et al. 2021).

Standard methods to measure total fluorine include combustion ion chromatography (CIC) and particle-induced gamma-ray emission (PIGE) spectroscopy (Schultes et al. 2019),

both of which were used in this study. The PIGE method has the advantage of preserving the samples intact, unlike CIC, which requires destroying part or all of a sample to extract enough material for testing. Both methods must be done in a laboratory and thus are not practical for rapid, portable, and inexpensive PFAS testing in the field.

Identifying specific PFAS, also called "analytes," requires a chemical analysis method known as liquid chromatography and tandem mass spectrometry (LC/MS-MS), which allows scientists to separate different chemical structures in an object or liquid and quantify them. This method, also used in this report, requires destroying the sample.

Measurement of fluorine using handheld XRF – A promising PFAS screening method

As concern over the widespread use of PFAS in consumer products grows, there is a critical need for rapid, cost-effective, and non-destructive screening tools outside of traditional laboratory settings. A handheld XRF optimized for fluorine detection is a promising method, offering immediate, in-field measurements without the high costs per sample, long turnaround times, and sample destruction typically required by laboratory-based methods.

Specifically, an XRF instrument determines elemental composition of an object by bombarding a sample with X-rays, causing different elements within the sample to emit an energy profile that defines its elemental makeup. Details about how a handheld XRF works are found at Bruker (2025a). Like the PIGE method, an XRF detects total fluorine and cannot measure specific PFAS. Fluorine detection, however, provides a good method to screen items, since high fluorine content suggests that PFAS are present.

Although a desktop XRF system has been successfully used for quantifying PFAS in consumer products (Roesch et al. 2023), this method is lab-based and requires significant time and resources to obtain results. To address this limitation, we assessed the ability of a new handheld XRF system to quantify the fluorine content in consumer products.

A handheld XRF validated for detecting fluorine as a proxy for PFAS could be a powerful tool to inform consumers about PFAS in consumer products (e.g., through community testing events in which individuals bring products for screening), to support sustainable purchasing, and to generate data to guide regulatory actions under programs such as Safer Products for Washington. It could also help identify PFAS-containing products to prioritize for replacement, especially in environments frequented by children such as child care centers, schools, and libraries—including via product replacement programs such as those run by the Washington Department of Ecology (Washington Department of Ecology 2025b). Finally, because the handheld XRF is portable, relatively easy to use, and does not require laboratory infrastructure, it has the potential to be adopted widely by government agencies, researchers, and nonprofits working to understand and reduce PFAS exposure.

Our research took advantage of recent advances in XRF technology that mitigate some of

the technical challenges associated with measuring fluorine with handheld XRF devices. Detecting fluorine with handheld XRF is technically challenging because fluorine is a light element that gives off a weak signal (i.e., emits a low amount of energy), which air, instrument windows, and other materials can absorb. Most handheld XRF instruments are designed to detect heavier elements such as lead and other metals, and they don't have settings or detectors that are sensitive enough to measure fluorine. However, the handheld XRF used in this study (Bruker Tracer 5g) has several features that improve its capacity to measure fluorine (Bruker 2025b). These include a more sensitive detector, full control over scanning settings, and improved shape that reduces the distance between the source, sample, and detector. Because air can interfere with the measurement of lighter elements like fluorine, this instrument has the ability to place a stream of helium between the sample and the detector to reduce signal loss.

This study focuses on developing a method to identify the presence of PFAS in products, not on assessing human exposure or health risk. The presence of PFAS in a product indicates a potential hazard, but not necessarily a risk to the user, since risk depends on both hazard and exposure. Our method therefore is most aligned with a hazard-based approach—seeking to avoid the use of harmful chemicals—which can help reduce risk proactively, even in the absence of complete exposure data. Assessing exposure in most cases requires a detailed evaluation of how PFAS might enter the body through various pathways, such as direct contact, ingestion, or inhalation, as well as how PFAS migrate from products into the home (e.g., from products or furnishing to indoor dust) or the environment (e.g., leaching out of discarded products in landfills to soil or water). While we do not attempt to quantify exposure in this study, our aim is to develop a screening method that can efficiently identify PFAS-containing products—providing an early warning of possible sources of exposure and associated health risks.

Methods

Community engagement

The UW and two King County teams, Public Health and Hazardous Waste, conducted community engagement and a poll to increase knowledge of PFAS in the community, gathered information on products of greatest concern, providing additional parameters to consider for product selection and testing.

We began by selecting categories of products for possible inclusion in the poll and subsequent testing. Based on a review of the literature and relevant regulations, we identified 12 categories of products likely to contain PFAS, which the UW and King County teams further narrowed to five main categories. We focused on products most likely to contain PFAS even if regulations will phase out the particular PFAS they contain in the coming years. We chose products based on the academic and grey literature, studies conducted by the State of Washington, and PFAS restrictions passed in the United States or European Union. We also included products that represent a variety of materials in order to understand PFAS usage in certain material types and to test the versatility of the XRF method with these materials. Lastly, we prioritized products that are used by children or other sensitive populations, especially if the products were likely to come into contact with hands or mouths, which increases the chances of ingestion.

Using online polling software, in English and Spanish, participants prioritized products for testing within the five main categories:

1. Children's products (9 products, out of which respondents could choose 5 items)
2. Cosmetics/personal care (7 products; respondents chose top 4)
3. Household items (5 products; respondents chose top 3)
4. Clothing/apparel (8 products; respondents chose top 5)
5. Containers/packaging (7 products; respondents chose top 4)

Poll participant recruitment

We conducted eight informal online sessions with 44 participants from 20 community-based and non-governmental organizations, academia, and local and state government. Table 1 summarizes the groups engaged and poll participants.

Community-based participants came from groups that had previously engaged with Public Health or Hazardous Waste, many of which had expressed interest in or requested more information on PFAS. They represented immigrant communities, neighborhoods experiencing health inequities, fishers, fish consumers, environmental groups, and children's health experts. We engaged groups focused on preventing childhood lead poisoning, those consulting with child care institutions, and organizations promoting healthy fish consumption. Non-governmental, academic, and government groups were selected based on their PFAS expertise or knowledge of local communities. They included representatives from local and state health departments, as well as academic researchers.

Table 1: Community engagement and poll participant counts

Type of organization	Number of groups engaged	Number of poll participants
Government/academic	6	15
Community-based organizations	9	14
Non-governmental organizations	4	6
Other community partners	6	9
Total	25	44

Note: Eight poll respondents who chose "other" were reassigned for consistency across groups when the poll participant was unsure about whether their organization should classify as NGO versus CBO.

Online meetings and poll design

Online meetings included a slide presentation that described what PFAS are, why they are used, how people are exposed, what is known about health risks and gaps in knowledge. It also explained the XRF method and how a reliable method to measure fluorine could be used by government agencies, academia, and the community.

Following each presentation, staff conducted a question-and-answer session and distributed a link to an anonymous online poll. The poll asked respondents to select the sector they represented and then choose which consumer products should be prioritized for PFAS testing within the five product categories. Participants could also write in additional items they would like to see tested.

Poll completion

Sixty-five participants started the poll (63 English, 3 Spanish), and 44 participants answered at least one o the product category questions. Thirty-eight participants (36 English, 2 Spanish) selected at least some products within all five categories, but participants did not always fill in the maximum number of choices in a category (e.g., they might have selected only three children's products even though they could pick up to five).

Poll analysis and results: What communities want us to test for PFAS

Votes were tabulated per product category and by participants' affiliation. For data analysis, responses to the sector question were then classified into two groups: community partners (n = 30), and government or academia (n = 14).

Figures 1 and 2 show the specific products that stakeholders prioritized for testing. Within each category, 10–17 o the 44 respondents provided additional recommendations on items to test. These included baby bibs, baby bottles, baby food, diaper cream, children's toys, furniture, household cleaners, utensils, food, items for pets, cases for phones and other devices, menstrual pads, underwear and bras, winter clothes, blinds, and bedding. They also suggested additional dental products, makeup, skincare, and hair products not on the original list.

Ranking of products for PFAS Testing

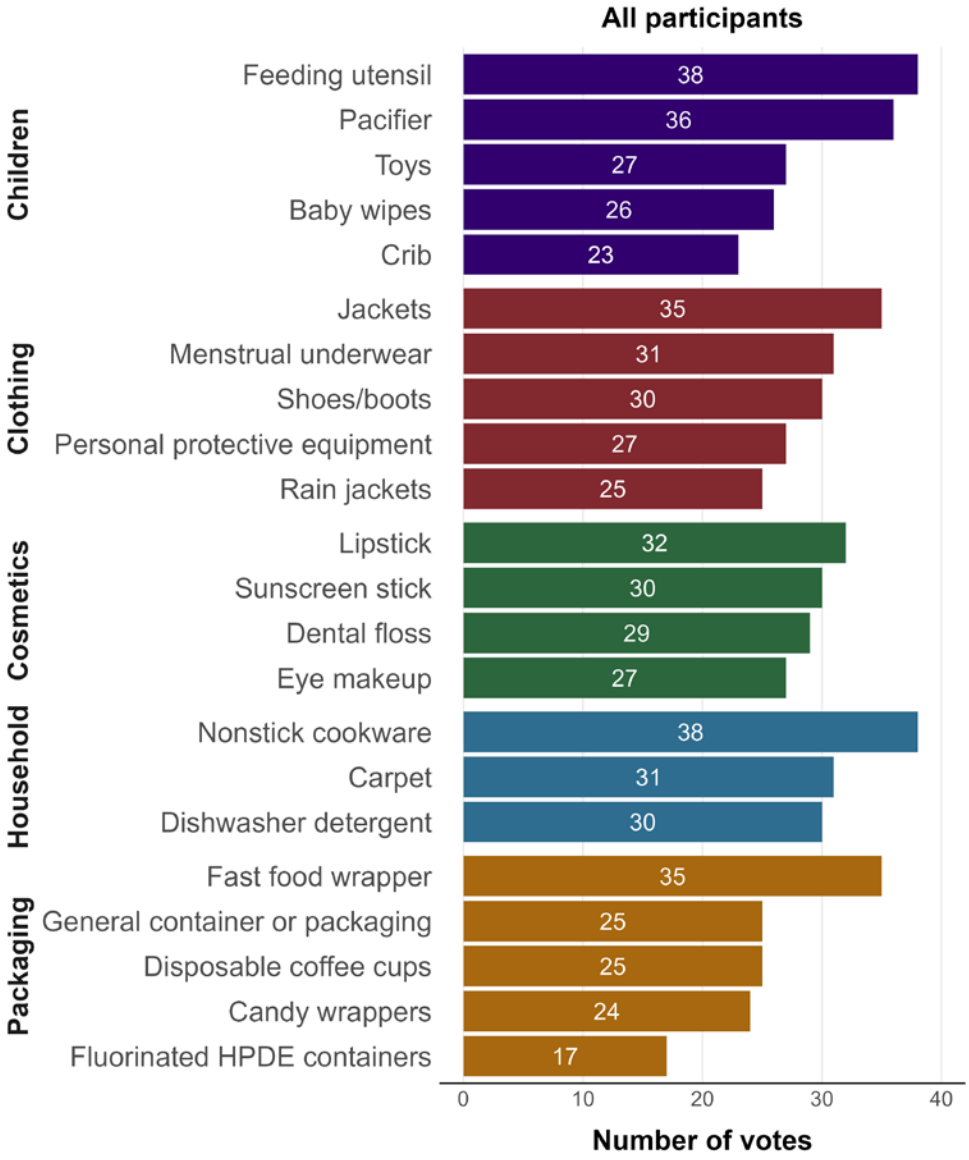

Figure 1: Ranking of products for PFAS testing within five key categories. *Note: The figure presents the number of top items in each category based on how many items were allowed to be selected in the poll.*

Community partners and respondents in government or academia had some notable differences in the products they chose; this is likely due to individuals' interactions with products and how familiar they are with the literature on PFAS in products, see Figure 2.

Ranking of products for PFAS Testing

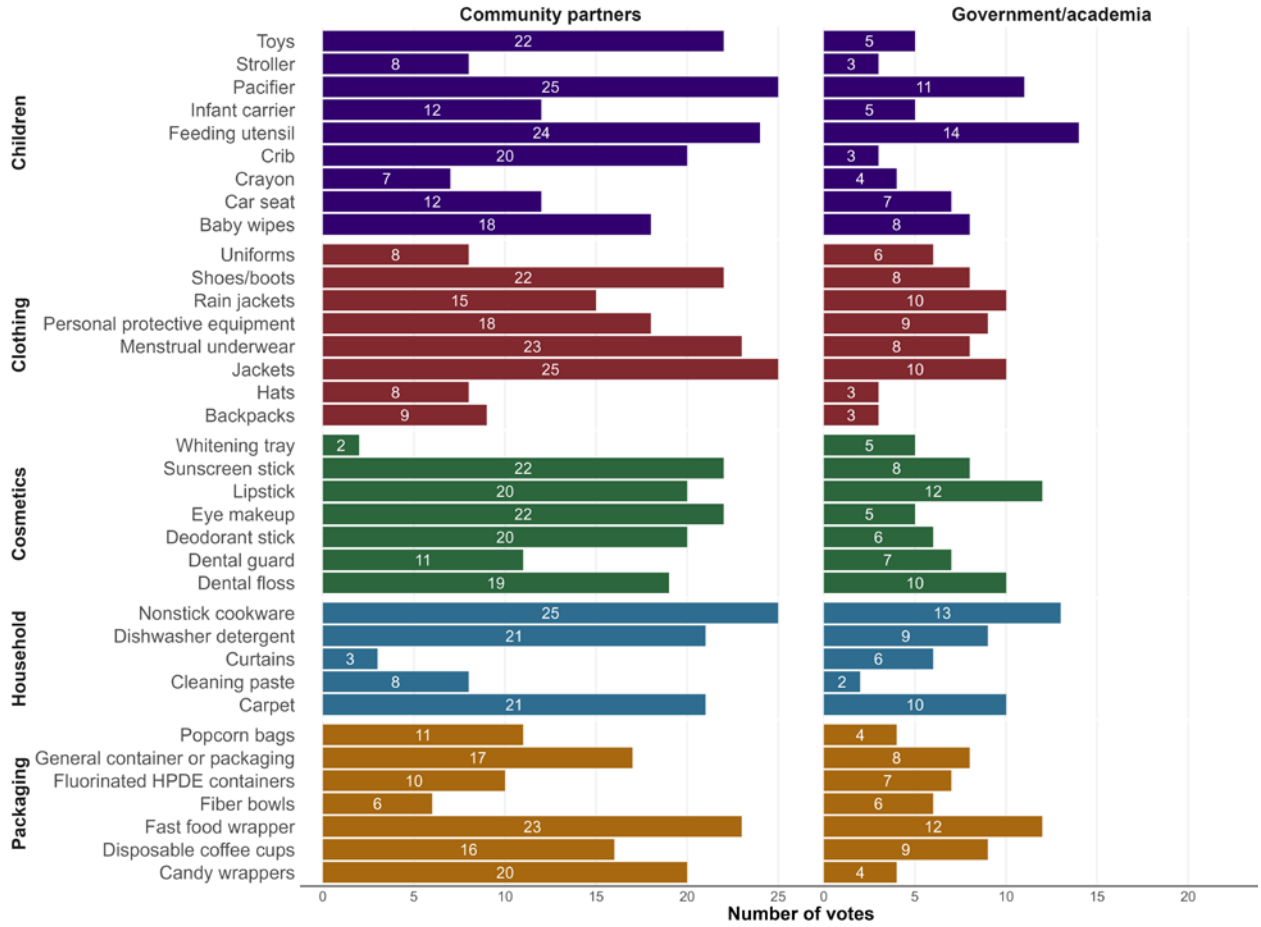

Figure 2: Ranking of products for PFAS testing by respondent category.

Community partners and government/academic stakeholders selected similar products in each category. For example, pacifiers and feeding utensils were the top-voted children's products; nonstick cookware and carpets were the top household products; fast-food wrappers were the top choice among containers and packaging; and jackets topped the clothing and apparel category. Slight differences were observed in cosmetics, with community partners showing the most interest in eye makeup, and government/academic participants ranking lipsticks higher.

Product selection, preparation, and testing

Product selection

Following the community-engaged prioritization of products, we then selected specific products to test. We specifically selected products that had previously tested positive for PFAS or were suspected to contain them, as well as others that were presumed to have no PFAS based on prior testing or product labeling—allowing us to include a range of fluorine concentrations to support XRF method development and assess potential "safer alternatives" (although we use this term to refer specifically to PFAS-free products, without having assessed potential hazards from other chemicals).

In addition to PFAS content, product selection was informed by the likelihood of human exposure (e.g., sippy cups that children place in their mouths), relevance to ongoing or proposed regulation, and product labeling claims that could indicate presence (e.g., "waterproof") or absence (e.g., "PFOA-free") of PFAS. We also prioritized items with high sale volumes—and thus a broad distribution among consumers—and inexpensive items, since they might be more likely to contain PFAS due to cost-cutting measures.

We purchased products through popular online retailers. We received other products (i.e., artificial turf, playground tile, carpet, and ski wax samples) from suppliers, manufacturers, and collaborators at the Department of Toxic Substances Control, Middlebury College, and King County Parks. See Appendix I for a complete list of selected products.

The final list included 92 consumer products for testing, 61 of which were suspected to have PFAS and 31 that were suspected to not contain PFAS. Up to two surfaces were tested for some products (e.g., the inside and outside textiles of a baby's boot), thus yielding 100 samples.

Sample preparation

We removed representative portions from the 92 products at the UW, resulting in 100 surfaces for testing. We purchased sufficient replicates of the products to be able to test samples without any preparation, which we called "intact samples." We also sent products to Eurofins Environment Testing Northern California, an independent and certified testing laboratory, for preparation into "homogenized samples"—a process to ensure uniformity across the three methods of identifying fluorine/PFAS (described further below). We, therefore, aimed to have both homogenous and intact samples for each product (Figure 3).

Homogenized samples were prepared by Eurofins to capture the materials used in the coatings or outer surfaces of the products, which are more likely to contain PFAS. Eurofins' scientists used clean scissors to cut approximately 1 cm square pieces from different areas of the products, or up to 5 grams of sample. When cutting was not possible (e.g., a ceramic pan), Eurofins scraped or pulverized the surface. Although these powder-based samples—along with other non-solid or sticky samples—were eventually tested by the PIGE, 32 samples

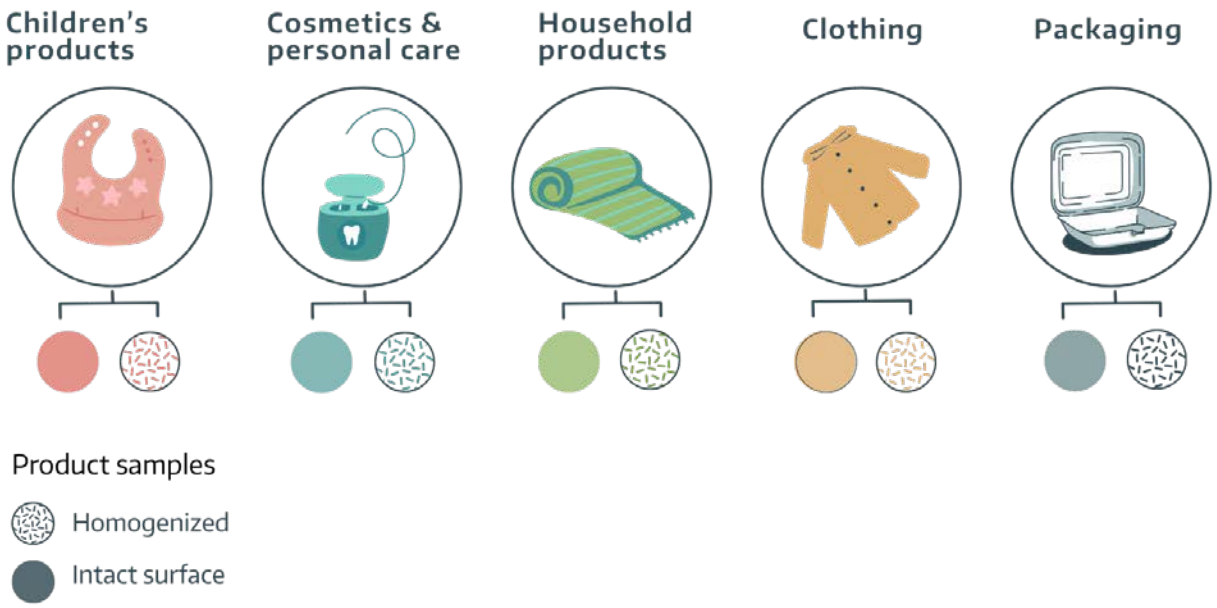

Figure 3. Choosing products and surfaces for testing.

did not end up being tested with the handheld XRF due to risk to the instrument; further experimentation will be needed to develop testing protocols for these types of samples, which was beyond the scope of this project.

Of the 100 samples sent to Eurofins, the laboratory was able to generate 98 homogenized samples. Two samples could not be homogenized, so a wipe was used to assess whether PFAS could be easily removed from the surface of these products and analyzed as a surrogate for the homogenized samples.

Sample preparation for handheld XRF analysis

The UW and King County teams processed 68 of the homogenized samples by adhering them to microscope slides for easy testing with a handheld XRF, as shown below in Figures 4 and 5. Other homogenized samples that are powder, gel, cream, oily, or sticky materials will be analyzed in the future, since they require additional method development to prevent damage to the instrument. Intact samples did not require any sample preparation.

Sample preparation for testing products for PFAS

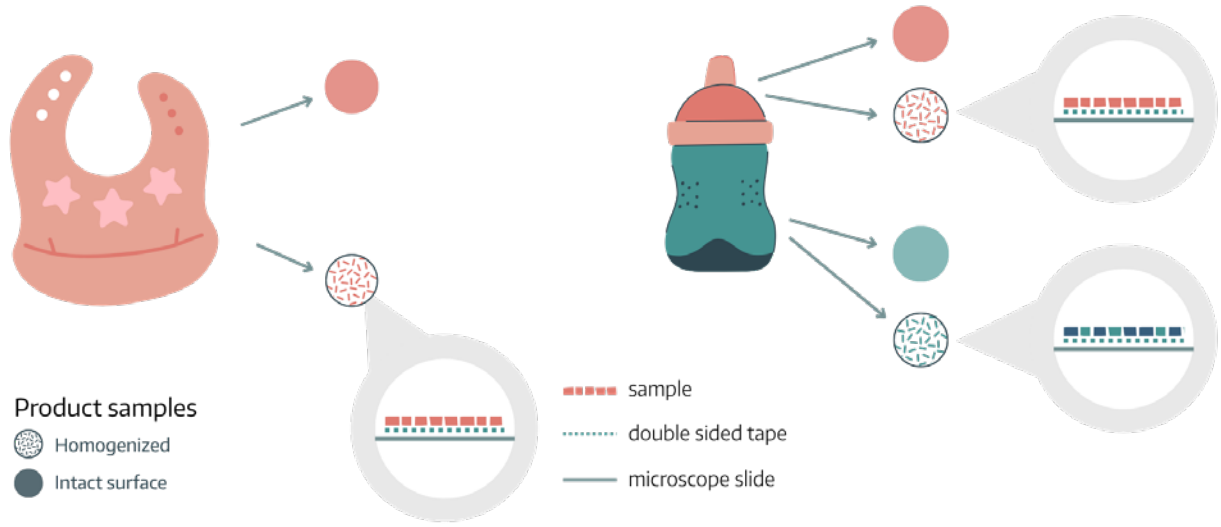

Figure 4. Schematic of preparation of "homogenized" samples for products with one or more surfaces for PFAS testing with the handheld XRF using microscope slides.

Examples of prepared "homogenized" samples for testing PFAS with handheld XRF

a)

b)

c)

d)

Figure 5. Photos of prepared slides with taped, homogenized samples of: a) nylon jacket, showing two distinguishable surface types; b) adhesive bandage, showing only one surface type; c) playground tile made of rubber, showing only one surface type; and d) artificial turf, showing two distinguishable surface types.

Sample testing strategy

To assess a handheld XRF as a screening method for total fluorine in consumer products, we first set up and optimized the handheld XRF (explained below), then we measured reference samples with known fluorine concentrations to be able to measure fluorine concentrations in samples (explained below). Lastly, we compared the handheld XRF results with three different techniques able to measure fluorine in consumer products, as shown in Figure 6: handheld XRF, PIGE, and CIC.

The UW and King County teams, in consultation with XRF expert Dr. Aaron Specht at Purdue University, performed the handheld XRF screening; Forever Analytical, a PFAS testing laboratory in South Bend, Indiana, conducted the PIGE screening; and Eurofins conducted the CIC screening.

Lastly, we also tested for 40 specific PFAS compounds to understand better which chemicals are most commonly found in the everyday products we tested. Eurofins conducted the LC/MS-MS (equipment shown in Figure 6).

Figure 6. Different methods and laboratories for testing products for PFAS for the optimization of the handheld XRF.

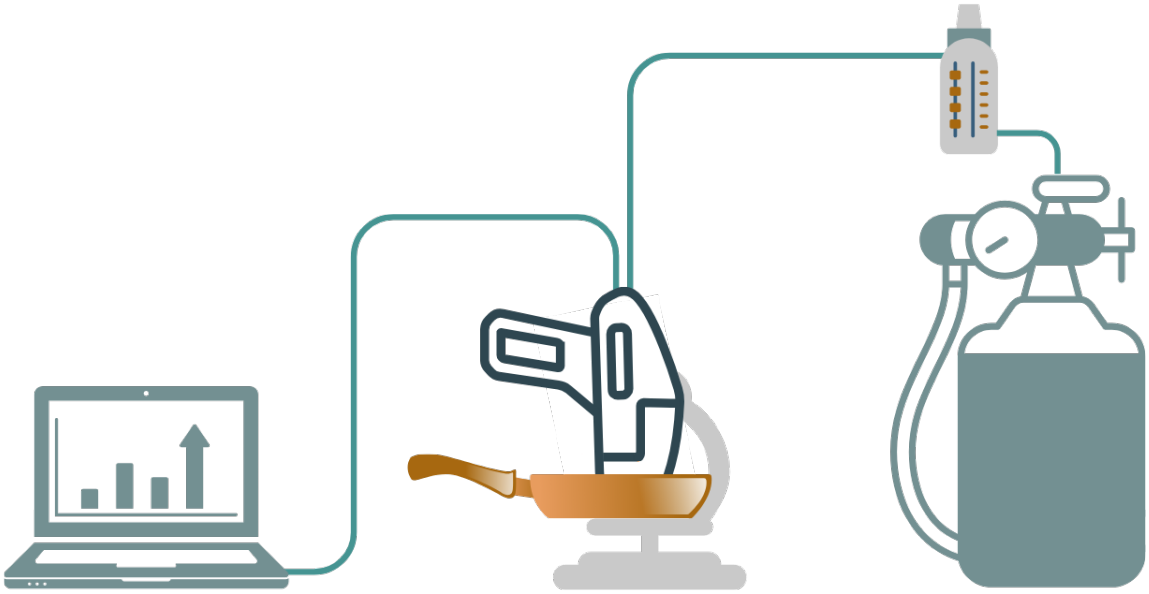

Figure 7. Testing products for PFAS set up with handheld XRF. *Note: For field deployment of the handheld XRF, a small helium tank designed for filling party balloons could be used instead of a large, compressed gas tank.*

Handheld XRF fluorine set up

As previously mentioned, XRF enables the assessment of objects' elemental composition without destroying the samples. We selected the only commercially available handheld XRF method capable of measuring fluorine (Bruker's TRACER 5g, Bruker AXS LLC, Madison, Wisconsin). We used two handheld XRF instruments, one belonging to the King County teams and one to UW.

As a first step, we set up the instruments following the manufacturer's recommendations (Bruker 2025c), as laid out in Figure 7 below. We also developed detailed standard operating and quality control procedures to help other organizations use handheld XRFs for fluorine measurement in the future. These procedures are available upon request.

XRF spectrum of negative and positive controls

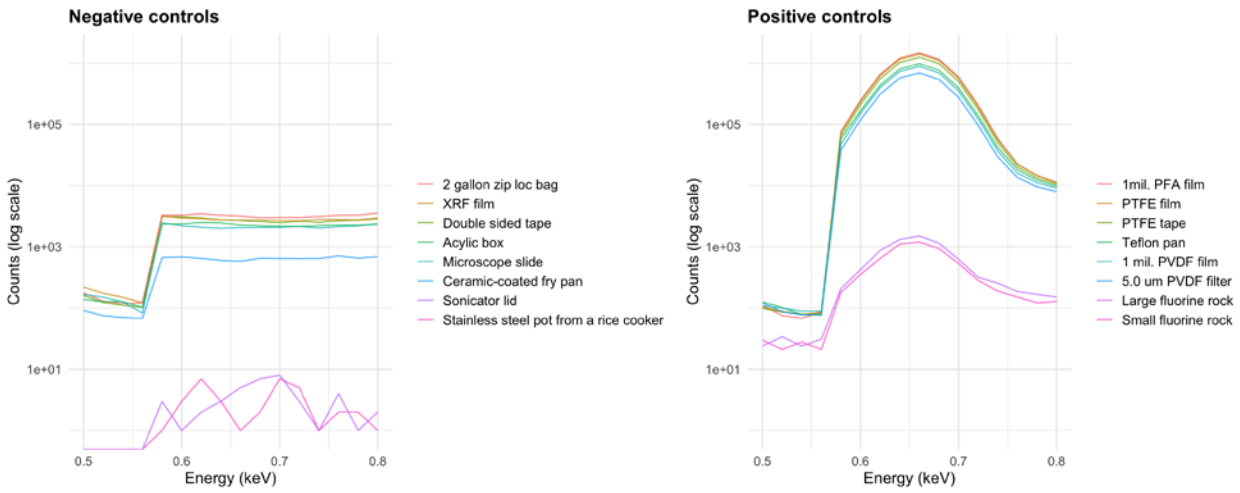

Figure 8. XRF spectrum from different objects known not to contain fluorine (left, negative controls) and known to contain fluorine (right, positive controls).

Handheld XRF fluorine optimization

Next, we tested objects known to be free from PFAS (e.g., microscope slides) and objects known to contain PFAS (e.g., nonstick pans and PFAS-containing tape) to optimize the handheld XRF device settings for detecting fluorine. We also scanned filters spiked with increasing known quantities of fluorine (aqueous sodium fluoride solution or NaF) to be able to accurately measure fluorine levels in the consumer products.

The signal obtained from an XRF instrument is visualized using a spectrum that displays the detector counts across different energy levels. Figure 8 shows the typical peak response when fluorine is present, known as a positive control, and when fluorine is absent, known as a negative control.

We then used positive controls to optimize the handheld XRF for fluorine, as detailed in Appendix II. Resulting optimized handheld XRF settings were: 12 kV voltage, 175 µA current, 5-min duration, helium atmosphere, no filters, and no window.

XRF spectrum calibration

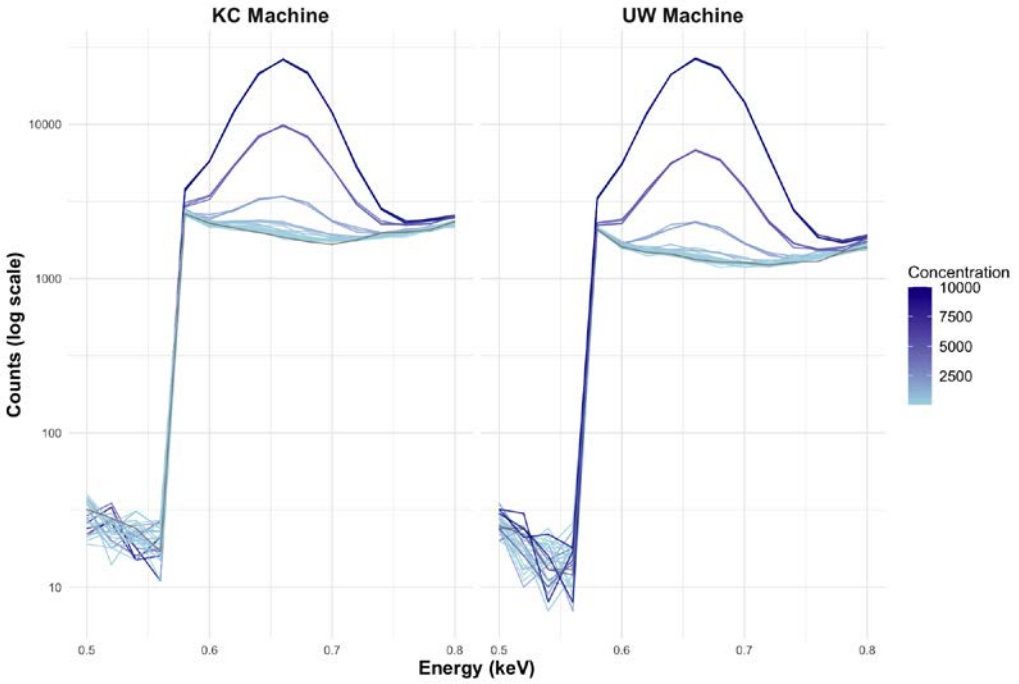

Figure 9. XRF spectrum from different levels of fluorine concentrations using the two handheld XRF machines. *Note: Optimized Bruker 5g handheld XRF settings were 12 kV voltage, 175 µA current, 5-min duration, helium atmosphere, no filters, and no window.*

Handheld XRF fluorine quantitation

To be able to quantitate fluorine using the handheld XRF, we needed reference samples. The UW Environmental Health Laboratory prepared these reference samples with known quantities of fluorine to be tested for purposes of quantitation and quality control (details in Appendix III). Each reference sample was measured using the optimized XRF settings to obtain its corresponding spectrum.

The spectrum at different levels of fluorine (Figure 9) indicate an increase in the peak size with increasing fluorine concentration. Peaks are easily distinguished at concentrations of 2,000 parts per million (ppm), 5,000 ppm, and 10,000 ppm. At concentrations of 500 and 1,000 ppm, elevated counts are visible in the fluorine peak region (0.64–0.68 keV), though a distinct peak is not observed—while at even lower concentrations (50, 100, and 200 ppm), the XRF output is more difficult to distinguish from that of the blank filter.

To evaluate XRF performance and compare it to other ways of measuring fluorine, we developed a process to convert XRF data into an estimated fluorine concentration for each sample. This involved generating a calibration curve, which is a mathematical equation that

shows the relationship between the XRF signal (i.e., the total number of X-ray counts detected in the energy range where fluorine appears) and known fluorine concentration (measured in parts per million, or ppm) based on what was added to the filter papers that were measured to show what counts equate to each ppm concentration known to be on that filter. The calibration curves for each of the two machines used are shown in Figure 10. These curves enable us to estimate concentration of fluorine in tested samples. Additional details about the calibration and optimization of the handheld XRF are included in Appendix II.

Handheld XRF response at different fluorine concentrations

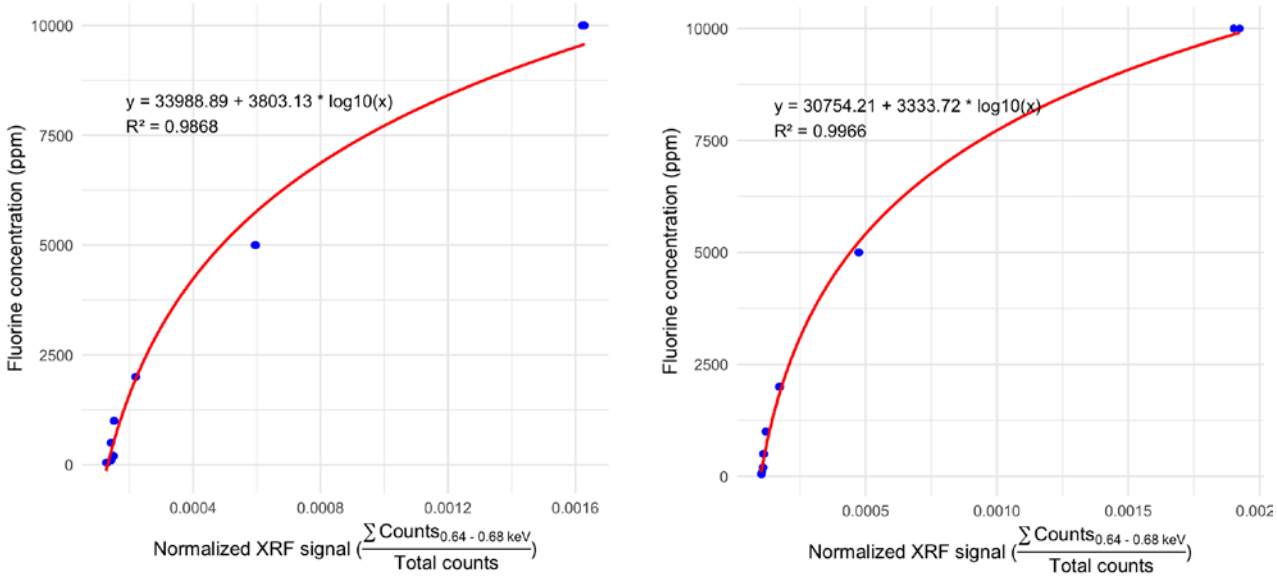

Figure 10. XRF detector response at different levels of fluorine concentration for each of the two handheld XRFs (King County machine left and UW machine right). *Note: The X-axis represents the sum of counts from the energy region of interest for fluorine, 0.64 keV to 0.68 keV, divided by the total counts. The Y-axis represents fluorine concentrations in parts per million (ppm). Data were fitted to a line using a logarithmic model, which was generated to estimate the levels of fluorine in product surfaces.*

Sample testing with the handheld XRF

Finally, we scanned both 86 intact and 68 homogenized samples (that could be tested with the current protocol, e.g., excluding samples homogenized to powder) using the optimized handheld XRF method. Each sample was tested in several locations of the surface area. Since the XRF currently does not automatically report fluorine concentrations in samples, we utilized the calibration calculation described above to estimate the fluorine concentration those counts represent (further detailed in Appendix III).

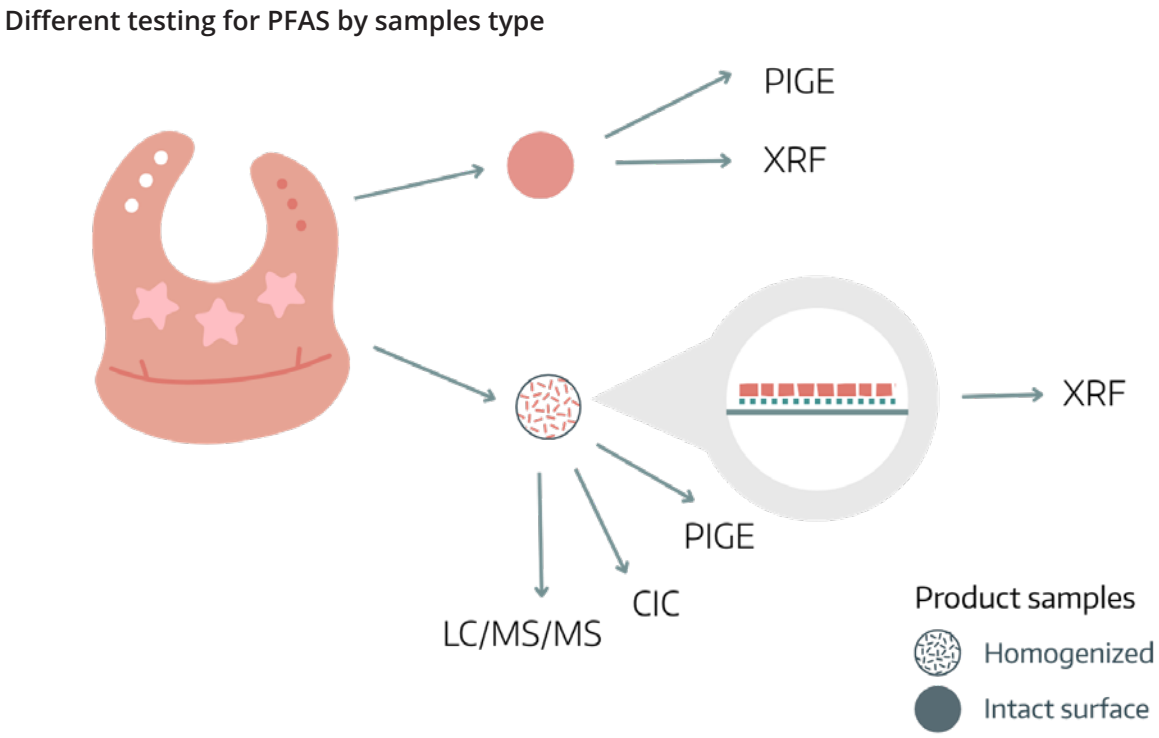

Figure 11. Different testing for PFAS by sample type.

It is important to note that our results suggest that further refinement is needed to improve XRF-based fluorine concentration estimates. For example, we obtained a wider range of estimated concentrations across different types of materials compared to the PIGE method. Additional calibration curves based on reference materials with different sample compositions will need to be tested and compared to enhance accuracy across the variety of products (e.g., calibration curves specific to material types such as plastics, metals, or ceramics). In the future, we also hope to further refine the mathematical relationship between XRF and concentration, as well as to incorporate this calculation into the instrument software itself, —which would greatly enhance the usability of this method in the field. However, this was beyond the scope of this one-year project, and all sample analyses in this report that rely on XRF-based fluorine concentration estimates should be considered preliminary and subject to future adjustments.

Sample testing with other methods

Forever Analytical measured total fluorine in all 98 homogenized samples and 12 intact samples using PIGE (Ritter et al. 2017; Peaslee et al. 2020), which is a non-destructive method that can detect low fluorine concentrations in both kinds of samples.

The Eurofins Laboratory measured total fluorine in 80 of the homogenized samples using CIC (Eurofins 2025), a destructive method that can detect low fluorine concentrations only in homogenized samples. Eurofins was not able to report results for the rest of the 18 homogenized samples because of extremely high levels of fluorine outside of their calibration range (i.e., this method was unable to measure materials with extremely high concentrations of fluorine, such as the PFAS-coated pans).

Finally, the Eurofins Laboratory also analyzed all of the 98 homogenized samples by liquid chromatography and tandem mass spectrometry (LC/MS-MS) to identify and quantify 40 individual PFAS compounds in the selected consumer products (Eurofins 2025; EPA 2025f,g)—so called "targeted" analysis. The method is destructive and can detect low concentrations of specific PFAS only on homogenized samples. For the two samples that could not be homogenized, a surface wipe was instead obtained and tested for the same 40 PFAS compounds. A list of the 40 PFAS analyzed by LC/MS-MS is included in Appendix IV. A representation of the type of samples and methods compared are graphically represented in Figures 6 and 11.

Results

Comparing handheld XRF with other methods that measure fluorine

We summarized fluorine concentrations by product category across the three different total fluorine methods—XRF, PIGE, and CIC. This allowed us to see whether the methods yielded consistent results. Note that the lowest detectable concentration of fluorine ("method detection limit" or MDL) was 20 ppm for both PIGE and the handheld XRF. For the XRF, the MDL is a preliminary estimated value calculated on initial testing conditions (see Appendix III for details). The CIC method detected fluorine is as low as 1 ppm.

Fluorine detection by method and by product

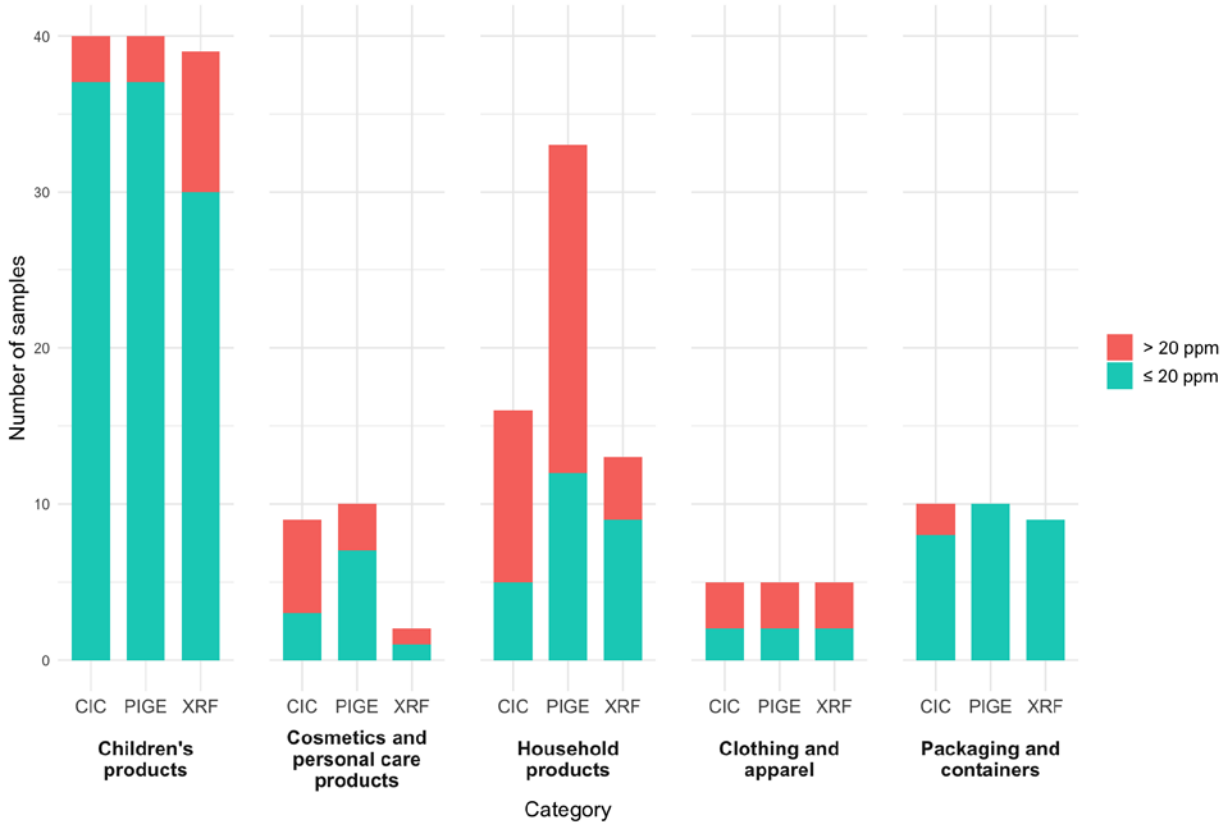

Figure 12. Proportion of fluorine detection by different methods and by product category (only "homogenized" samples shown). *Note: Total fluorine analysis by CIC could not be performed for 20 samples due to challenges related to either sample not being possible to homogenize or the high levels of fluorine exceeding the instrument's ability. Furthermore, 32 samples were not tested by XRF due to challenges in preparing non-solid materials or because homogenized materials could not be achieved. Three samples—one from children's products, one from household products and one from clothing and apparel—exhibited excessively high fluorine signals in CIC, making accurate quantification impossible. For these, we used the reported estimated concentration by the CIC method.*

We present data in different ways to make comparisons among the three methods. Specifically, we applied a threshold of 20 ppm—the MDL by PIGE—to evaluate the effectiveness of each method for detecting fluorine in the samples. This allowed us to determine how many samples exceeded this concentration (i.e., detected fluorine) across the PIGE, CIC, and handheld XRF. The CIC method detected fluorine above 20 ppm in 25 out of 80 samples tested (31%). PIGE detected fluorine above 20 ppm in 30 out of 98 samples (31%). The handheld XRF identified fluorine above 20 ppm in 17 out of 68 samples (25%). Figure 12 shows general agreement in detection across the three methods, with the highest agreement in the clothing and apparel and packaging and containers categories.

Table 2 summarizes how XRF fluorine results for all homogenized samples compared with those from the PIGE and CIC methods. Most samples (61%) were classified as negative for fluorine across all three methods, suggesting good agreement on non-detects when fluorine was below 20 ppm. Fluorine was detected by all three methods in 11% of the samples, with very high average fluorine concentrations reported by PIGE and CIC, suggesting strong agreement across methods when fluorine levels are very high.

Four samples were identified as fluorine positive only by CIC, which could be due to samples having low fluorine content or fluorine that was not on the surface where XRF and PIGE can measure it. Unlike CIC, which measures fluorine in the whole sample, PIGE can only measure fluorine between 100 to 250 µm (roughly the diameter of 1 to 3 human hairs) into the surface of objects (Schaider et al. 2017), while the handheld XRF has been reported to measure fluorine only to a surface depth of 1 µm (Labquip 2025).

Table 2. Comparison of fluorine detections across handheld XRF, PIGE, and CIC methods ("homogenized" samples).

XRF detection*	PIGE detection*	CIC detection*	Number of samples	% of samples	PIGE concentration mean (range)	CIC concentration mean (range)
No	No	No	40	60.6	2.1 (0–9)	6.0 (0.4–20)
No	No	Yes	4	6.1	12.1 (2.5–20)	143 (78–230)
No	Yes	Yes	6	9.1	64.8 (23–126)	222 (32–480)
Yes	No	No	8	12.1	2.2 (1–7)	4.2 (0.4–8.8)
Yes	No	Yes	1	1.5	13 (13–13)	57 (57–57)
Yes	Yes	Yes	7	10.6	4,043 (26–26,405)	4,927 (76–30,000)

*Fluorine was designated as detected if fluorine concentration was above 20 ppm.

In six samples, XRF failed to detect fluorine that both PIGE and CIC detected. Concentrations in these samples ranged from tens to low hundreds of ppm, which may be challenging for XRF to detect, depending on the material and type of surface. For eight samples, only XRF detected fluorine despite the low concentrations (<10 ppm) reported by the other methods, which suggests these are false positives. Lastly, XRF seemed to identify fluorine in one product in which CIC also found fluorine but PIGE did not.

To understand how the handheld XRF performed compared to other methods, we also looked at how closely the results matched by calculating correlations—a statistical measure of how well two data sets agree—between the different methods for measuring total fluorine. These results, as shown below in the left panel of Figure 13, suggest that the results from XRF are statistically significantly associated with those from PIGE and CIC. Still, the strength of the relationship is moderate, although stronger if considering matrix effects (i.e., differences in the materials of the surfaces), shown on the right panel of Figure 13.

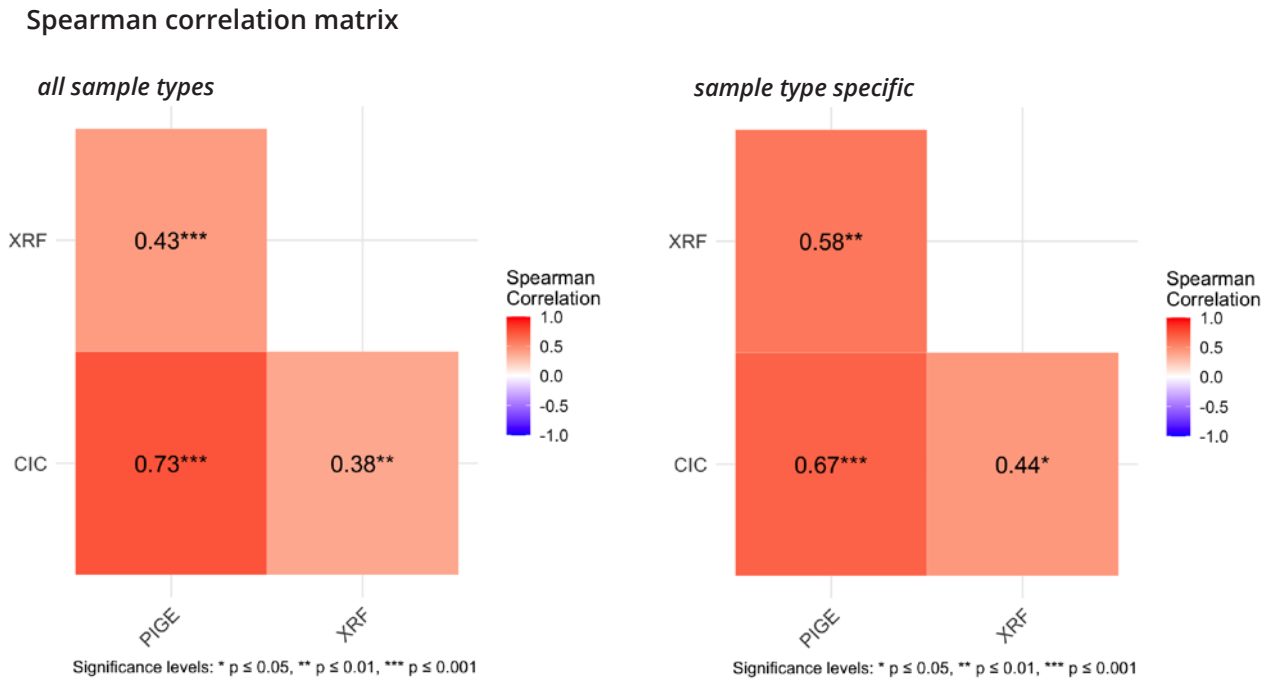

Figure 13. Correlation matrix (Spearman's correlation) between XRF, PIGE, and CIC fluorine detection results using averaged results from replicate measurements for all products (left) and for products with similar matrices (right) (only "homogenized" samples shown). Note: This figure shows Spearman's correlation coefficients, which describe how similarly different methods rank the concentrations of fluorine in the products. A value close to 1 means the two methods tend to rank samples in the same order (higher concentrations in one method also tend to be higher in the other). A value near 0 means there is little to no relationship in the rankings, and a value near -1 means the rankings are opposite. For example, the correlation between XRF and PIGE was 0.43, suggesting a moderate tendency for the two methods to rank samples similarly.

Accounting for the material of tested surfaces improves method comparison

Matrix effect refer to how the type of material being tested can influence results. For example, the surface texture, density, or chemical makeup of a product can interfere with how well the instrument detects fluorine, making it harder or easier to get accurate readings across different materials. While other PFAS methods extrapolate total fluorine using a liquid fluorine standard (Miller et al. 2024; Sanyal & Misra 2018), we spiked cellulose filters with the same standard (NaF) to create solid calibrants. Although using the same calibrants for all tested products—cellulose filters spiked with varying levels of NaF—

provided consistency, they do not fully represent the composition of all tested products, and matrix effects are expected to influence XRF fluorine quantitation. Our calibrants were prepared similarly to the liquid NaF standard spiked onto paper in PIGE-based cosmetic measurements reported by Whitehead et al. (2021).

To minimize matrix effects, we created a subset of the data including only samples with similar matrix characteristics. Specifically, we retained samples with certain XRF parameter readouts (i.e., deadtime percentages reported by the instrument run that were below 30%). Deadtime reflects the time the detector is not measuring x-rays during the run because the detector is getting too many photons from the sample. For example, high density materials (e.g., coated metal) tend to have a higher deadtime compared to lower density materials (e.g., textiles). A threshold of a deadtime below 30% primarily captures low-density, paper- and clothing-based products more comparable to the filter paper used in calibration. The correlations between XRF and both PIGE and CIC improved when matching the matrix/materials of the samples. Thus, considering the matrix of the samples enhances the accuracy and comparability of XRF results (right panel of Figure 13).

Characterizing agreement between handheld XRF and laboratory-based methods

We evaluated the agreement between the handheld XRF results and those obtained using PIGE and CIC methods, assuming that PIGE and CIC correctly identified whether F was present or absent. We employed a set of commonly used accuracy measures to assess the ability of XRF to correctly classify samples as containing fluorine or not. We calculated sensitivity, which is the percentage of samples that are correctly identified as having fluorine ("true positives"), to assess how well XRF detects fluorine when it is truly present. We calculated specificity, which is the percentage of samples that are correctly identified as not having fluorine ("true negatives"), to assess how well the XRF avoids detecting fluorine when it is not present. An accuracy metric represents the overall proportion of correct classifications, whether true positives or true negatives. Lastly, a Cohen's Kappa statistic was calculated to measure the degree of agreement between XRF and other methods after accounting for the agreement that could occur by chance.

Table 3. Detection of fluorine comparison by handheld XRF and PIGE methods ("homogenized" samples)

XRF fluorine detection (>20 ppm)	PIGE fluorine detection (>20 ppm)		
	Yes	No	Total
Yes	7	10	17
No	6	45	51
Total	13	55	68

Table 4. Detection of fluorine comparison by handheld XRF and CIC methods ("homogenized" samples)

XRF fluorine detection (>20 ppm)	CIC fluorine detection (>20 ppm)		
	Yes	No	Total
Yes	8	8	16
No	10	40	50
Total	18	48	66

Tables 3 and 4 present fluorine detections in homogenized samples by handheld XRF compared to what other methods PIGE and CIC, were able to detect too. For example, in Table 3, the handheld XRF identified 17 positive samples, out of which PIGE only detected 7. Similarly, in Table 4, the handheld XRF identified 16 positive samples, out of which CIC only detected 8.

Table 5 presents results of diagnostic accuracy measures, with 100% an ideal measure of agreement. Overall, XRF performed better at ruling out the presence of fluorine compared to detecting it.

Specificity was relatively high compared to both methods: the handheld XRF correctly identified the absence of fluorine in 82% of samples that PIGE also classified as non-detects, and 83% of samples that CIC classified as non-detects. This suggests the handheld XRF was relatively good at ruling out the presence of fluorine in products when it is truly not present.

Sensitivity was lower (54% vs. PIGE, 44% vs. CIC), meaning XRF missed a notable portion of samples that PIGE or CIC identified as having fluorine. Accuracy was moderate, with XRF correctly classifying 73–77% of samples compared to PIGE and CIC. There is also a fair agreement between the methods beyond what would be expected by chance, as indicated by Cohen's Kappa values of 0.37 (vs. PIGE) and 0.31 (vs. CIC). As a comparison, A Cohen's Kappa (κ) value of 0.81 or higher would have indicated an "almost perfect" agreement between methods while values closer to 0 suggesting little to no agreement.

While most of our analyses have focused on comparing whether fluorine was detected or not across methods, we also examined differences in fluorine concentrations obtained by each method and across different product categories (Figure 14). Estimated fluorine concentrations using the handheld XRF were within similar ranges of concentrations measured with PIGE and CIC but included negative values and overall had higher variability. As noted throughout, we consider the estimated concentrations for XRF as preliminary and subject to further adjustment.

Table 5. Performance characteristics of handheld XRF fluorine detection compared to PIGE and CIC methods ("homogenized" samples)

Comparison	Sensitivity	Specificity	Accuracy	Cohen's Kappa
XRF vs. PIGE	53.8%	81.8%	76.5%	0.32
XRF vs. CIC	44.4%	83.3%	72.7%	0.29

Fluorine concentration distributions by method and by product

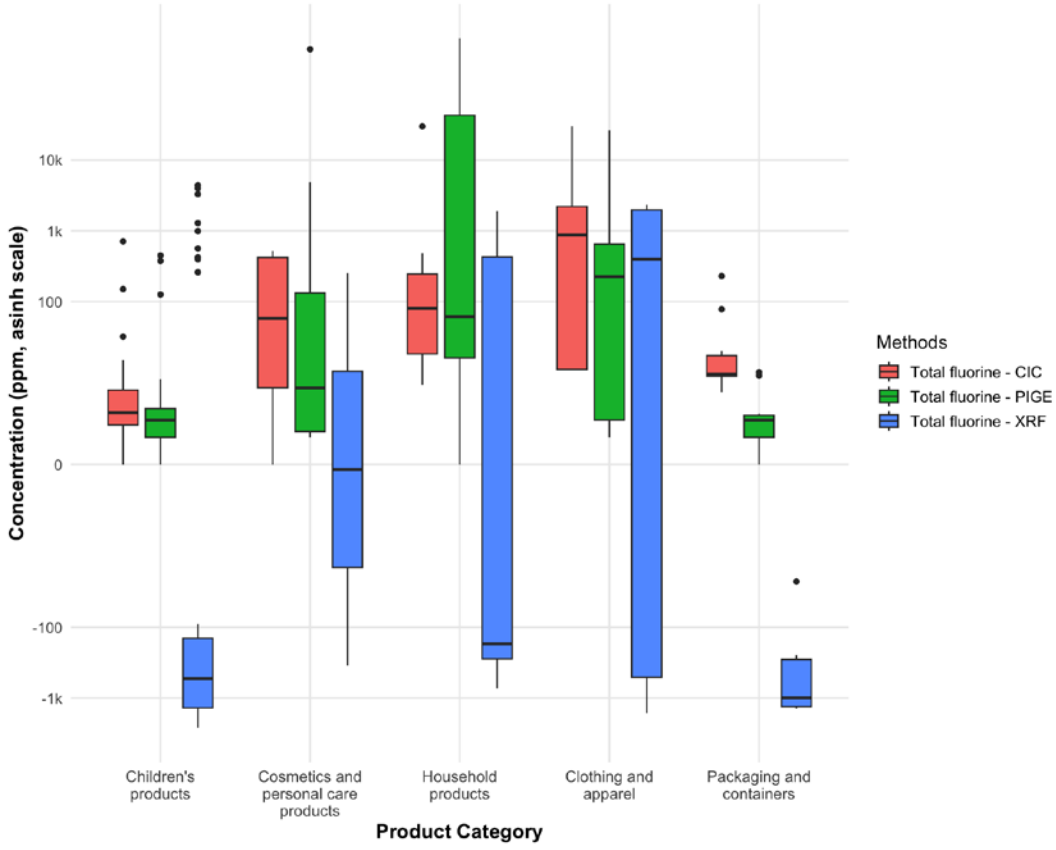

Figure 14. Fluorine concentration distributions measured by different methods and by product category (only "homogenized" samples shown).

Intact versus homogenized samples by handheld XRF and PIGE methods

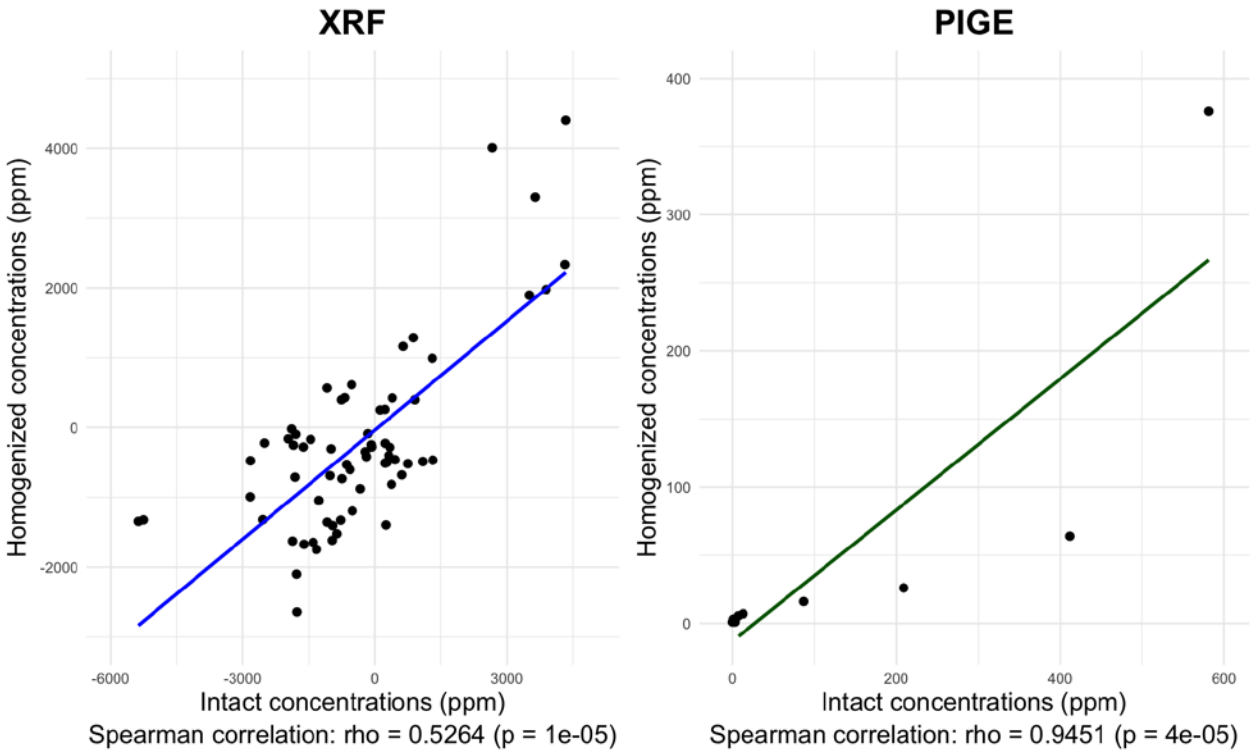

Figure 15. Comparison of fluorine measurements using prepared "homogenized" samples versus intact samples using handheld XRF (left) and PIGE (right).

Effect of sample preparation on fluorine detection

We examined how sample preparation affects fluorine detection by handheld XRF by comparing total fluorine results from intact and homogenized versions of the same samples using both PIGE and handheld XRF (Figure 15). This analysis helped us assess whether handheld XRF might be suitable for field-based testing of intact consumer products. The comparison included 66 matched pairs for XRF and 10 matched pairs for PIGE. To evaluate how similarly each method ranked fluorine concentrations between the two sample types, we used Spearman's correlation. The correlation was moderate for XRF (ρ = 0.53) and strong for PIGE (ρ = 0.95). A scatter plot is also provided to visually characterize the relationship between the two sets of measurements.

PFAS in products: Examining specific PFAS in products

To evaluate XRF's usefulness as a screening tool for PFAS in products, we examined the types and frequencies of specific PFAS analytes present in products, as identified by targeted laboratory testing (i.e., LC/MS-MS). This provides important context for interpreting the total fluorine measurements from the handheld XRF. Details of the results from LC/MS-MS are in Appendix I.

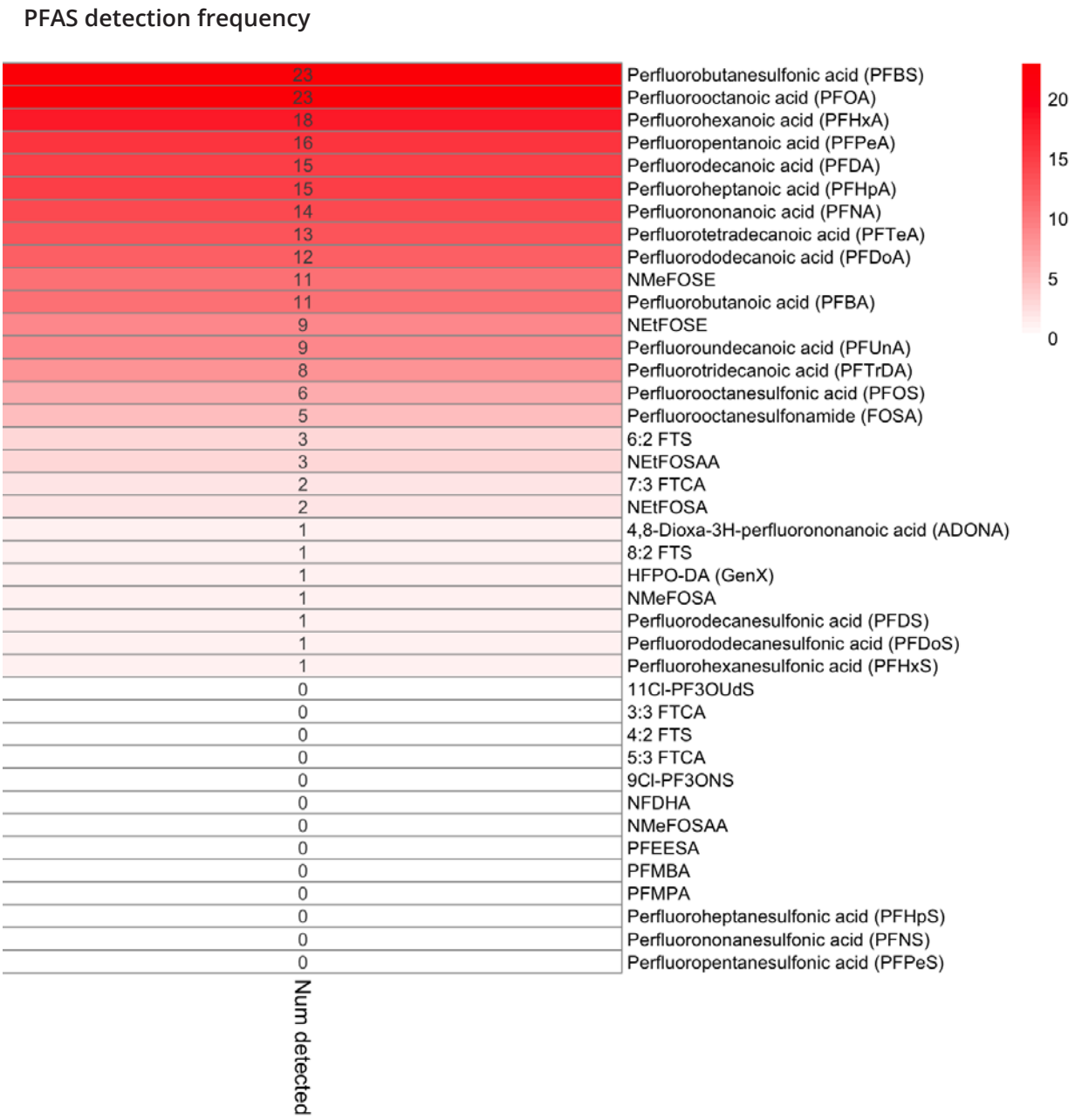

Figure 16. PFAS detection frequency by PFAS measured in 98 "homogenized" and 2 wipes samples (total of 100 samples from 92 products).

We ranked the PFAS analytes, measured with LC/MS-MS, by their frequency of detection across all samples (Figure 16). Perfluorobutane sulfonic acid (PFBS) and PFOA were the most frequently detected, with each found in 23 samples. As a reference, this lab method measures PFAS analytes at much lower levels than the total fluorine methods—in the parts per billion (ppb) level—while total fluorine was considered "detected" at concentrations above 20 ppm (approximately ten thousand times higher).

PFAS detection frequency by product category

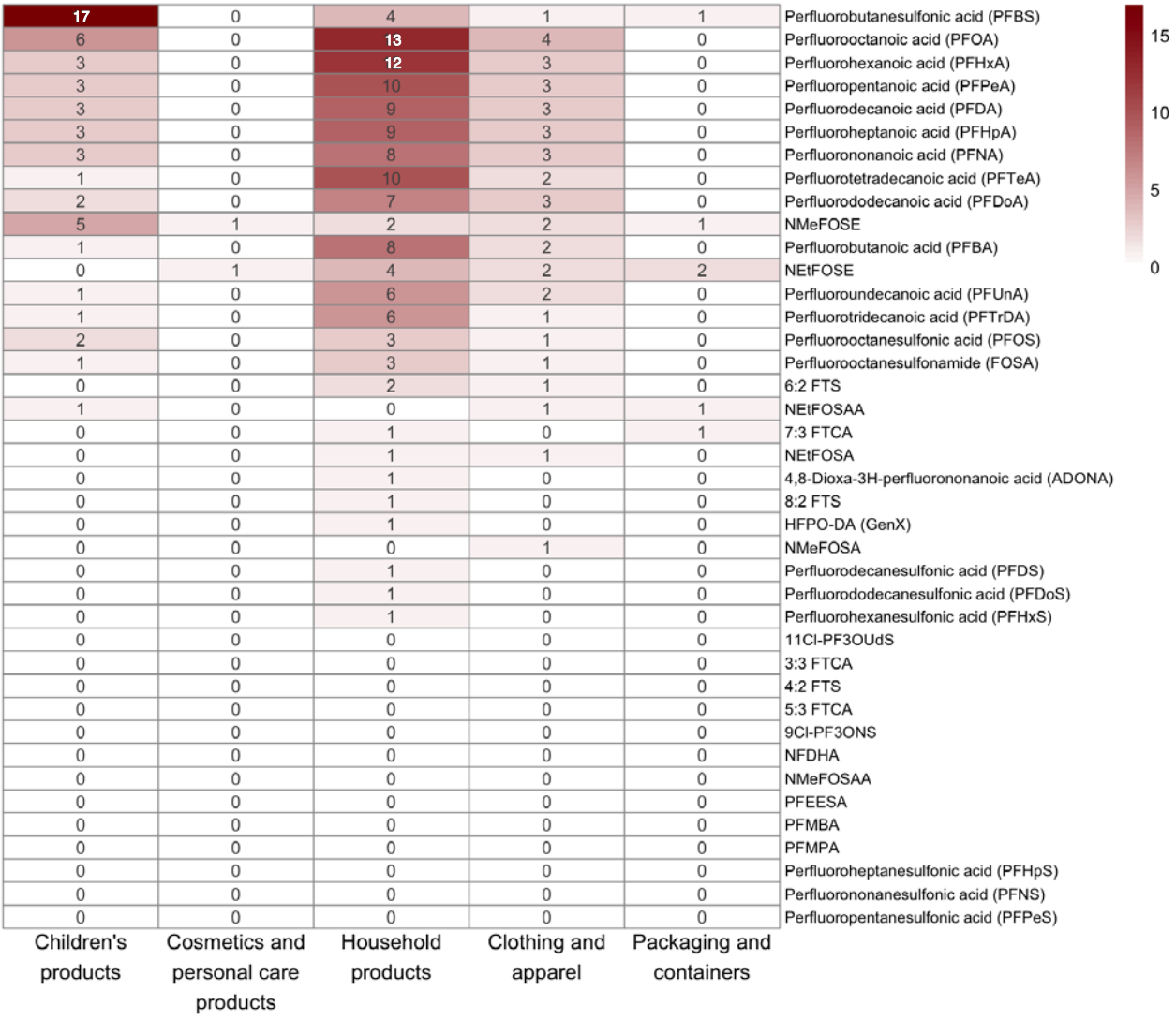

Figure 17. PFAS detection frequency by product category (98 "homogenized" and 2 wipes samples, for a total of 100 samples from 92 products). *Note: Surface wipe samples were collected and analyzed for two products in the household category, as Eurofins could not generate homogenized samples due to matrix-related challenges.*

We also examined how often different PFAS compounds were detected in each product category (Figure 17). For example, PFBS was commonly detected in children's products, while PFOA and perfluorohexanoic acid (PFHxA) were more frequently found in household products.

The below stacked-bar graph, Figure 18, summarizes the number of samples in each product category with at least one PFAS analyte detected versus those without any PFAS analytes detected. Among the five categories of interest, more than half of the samples in children's products, household products, and clothing and apparel had at least one PFAS analyte detected.

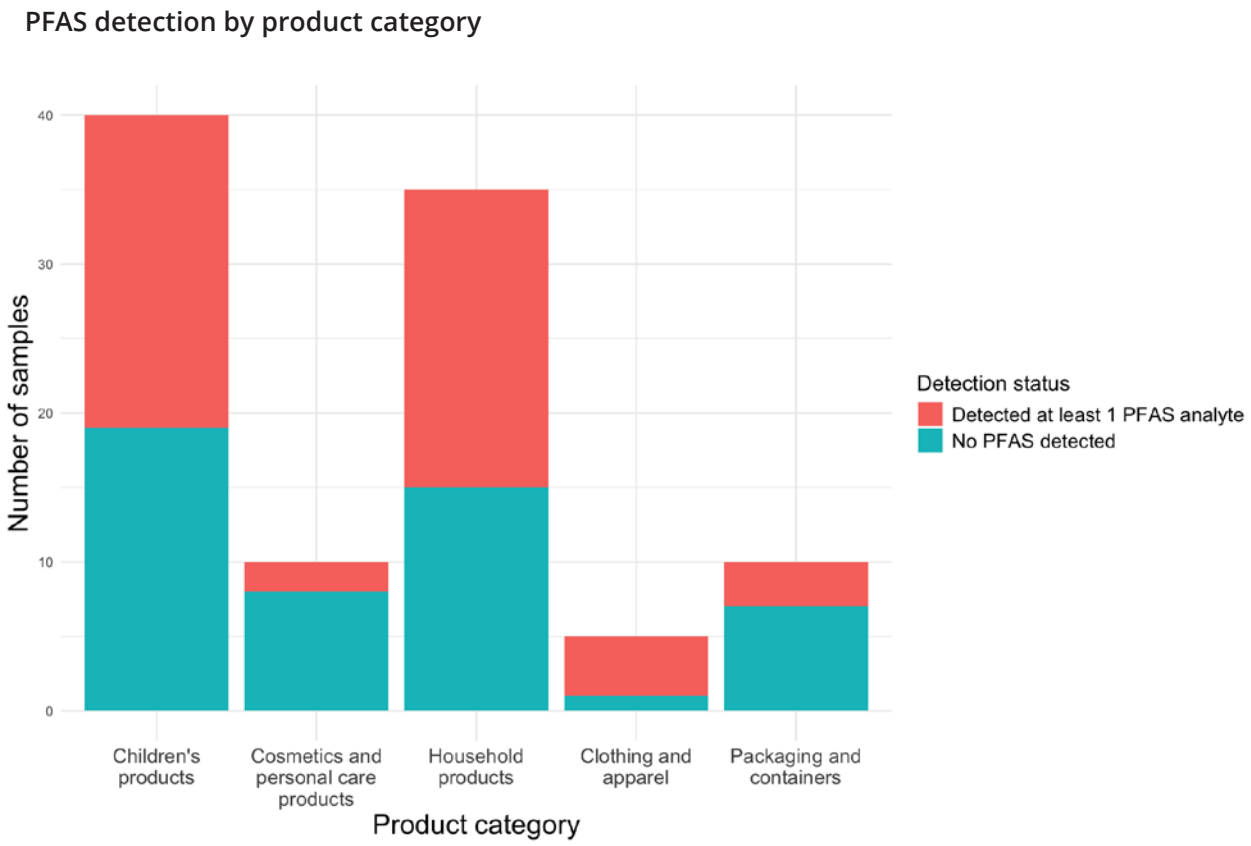

Figure 18. PFAS detection by product category (98 "homogenized" and 2 wipes samples, for a total of 100 samples from 92 products).

We also compared 62 samples suspected to contain PFAS and 38 samples we classified as not likely to contain PFAS—100 samples obtained from 92 products—because of marketing, labeling, or prior published testing. Among the suspected PFAS-positive samples, 39 (63%) had at least one PFAS analyte detected, whereas 11 (29%) of the potential no-PFAS products had at least one PFAS compound.

Discussion

Incorporating community PFAS concerns into study design

Engaging partners and centering the voices of different local communities ensured the research process included their interests. Through this process, we were able to leverage the ongoing community-based work of King County teams. This approach maximized the impact of available resources while ensuring that the findings were relevant and actionable. The positive response during the community engagement phase was only possible because of King County teams' strong, trusting, and long-standing relationships with many community-based organizations.

The products we tested included the top-voted products from all five categories. Given the limited number and types of samples we could analyze, it was challenging to include all products the community prioritized. However, their input will continue to be included in future studies. Although the sample of products tested was not exhaustive, we selected products that supported method development while reflecting real-world relevance, as those recommended by the community. We included testing samples with known positive and negative PFAS content, which was crucial when optimizing our method and comparing it with other methods. We prioritized products that were both inexpensive and popular in order to reflect potentially common exposures. We also attempted to cover a broad range of products likely to be of concern for PFAS exposure, relevance to chemical policy, or potential safer alternatives.

A notable difference in products recommended for priority testing by community participants and government or academic institutions was observed in the cosmetics category. The community selected eye makeup as a priority, whereas this was not among the top five products prioritized by government or academic participants. This difference could be due to the known interest of several community groups involved in our engagement on the topic of lead (Pb) in eyeliners. The technical experts, on the other hand, have a greater understanding of currently available data regarding PFAS content and exposure, and some may have been aware of the XRF machine's limitations for testing various materials. The differences between groups should be further explored so that future testing can be adapted to address specific cultural or other community-based concerns.

The results of the poll and PFAS testing will inform future communications about PFAS exposure in consumer products, particularly with concerned communities and nonprofit groups. Poll results will enable the UW and King County teams to develop interventions to reduce PFAS exposures in collaboration with their community partners. Additionally, we aim to engage with ongoing efforts at the local, state, and national levels to restrict PFAS

usage in products, such as the Safer Products for Washington program. We also aim to screen additional products of concern that can inform actions by community groups (e.g., product replacement events, tailored guidance to reduce exposures) and by government agencies (e.g., legislative priorities, local and state policies, guidance, interventions, or research). A community-focused report highlighting the results for products of concern identified in the poll will be developed and disseminated to participants as a future action.

Setting up the handheld XRF for fluorine detection

While we worked to improve the performance of the handheld XRF for fluorine detection, we aimed to strike a balance between accuracy, sensitivity, and practicality. For example, when choosing the sample run time (5 minutes), we considered the ability to process multiple samples quickly. Although a more extended run may have resulted in improved sensitivity, it also means that the method developed would not be as practical for field deployment. On the other hand, the XRF's ability to easily detect fluorine in some products with high surface fluorine (e.g., nonstick cookware) suggests that scan durations for certain products could be much shorter than 5 minutes while maintaining high detection ability.

This initial effort utilized the manufacturer's recommendations for low-energy elements to create an optimal general method. Elemental fluorine has a very low atomic number, resulting in a signal that is easily blocked by the XRF's protection window and the air. To capture fluorine's weak signal, the handheld XRF must be operated without a protection window and with a helium purge (in which air between the detector and the sample is replaced with helium so that more signal can be detected). Therefore, in this project, we focused on products made from solid materials that are straightforward to test. Innovative sample preparation methods will be needed to determine fluorine levels using XRF in non-solid materials, such as liquids, gels, creams, powders, and other non-solid, oily, or sticky matrices. These methods have trade-offs but may offer advantages in certain situations. For example, although applying an additional thin film may limit the XRF's ability to detect lower fluorine levels by increasing the attenuation of the fluorine signal between the sample and the detector, we are currently investigating this method for sample preparation to enable the measurement for non-solid and sticky samples while avoiding detector damage. Lastly, in the future, testing other setups, such as a vacuum chamber, could further improve detection capabilities.

Fluorine quantitation with the handheld XRF

Despite the need for further validation, the quantitation of fluorine concentrations using the handheld XRF provided preliminary concentration results that compare reasonably well with other techniques known to accurately measure total fluorine, such as PIGE and CIC. A logarithmic equation provided the best fit from the results of the fluorine-spiked filters.

Challenges of detecting low fluorine levels with the handheld XRF

Although our estimated MDL calculations suggest that the handheld XRF can detect as little as 20 ppm—the same as PIGE—we had difficulty distinguishing a visual peak in the energy spectrum data at these low concentrations. The XRF did not detect fluorine in several samples that PIGE and CIC classified as having low fluorine concentrations. The background interferences from the different materials likely contributed to obscuring the signal. Thus, a correction would be needed to adjust for the lowest range of concentrations. To address this challenge, we are currently conducting additional experiments. It would be desirable to perform calibrations for specific matrices to refine the quantitation models further and improve the confidence in our measurements of low fluorine concentrations. Despite these limitations, the handheld XRF was able to detect fluorine with low to moderate certainty when it was present in products and was good most of the time at ruling out the presence of fluorine when it was absent. However important to note is that both PIGE and CIC measure essentially different parts of the sample when compared to the XRF—the XRF measures only the top layer, while PIGE measures much deeper into the sample, and CIC measures the whole sample. These fundamental differences in sampling depth likely explain some of the discrepancies observed across methods.

Given the substantial advantages of handheld XRF, such as portability, real-time results, and significantly lower costs compared to lab-based methods, we believe further refinement of this method is warranted. Although our results show clearly that XRF can detect fluorine in some products based on our current protocol, we think that further method development could enhance its utility as a practical screening tool for a wider range of applications.

Limitations of XRF-PIGE-CIC comparison

The results from the handheld XRF compared reasonably well (a moderate but statistically significant association) with those from PIGE and CIC. One of the main limitations of the study design for comparing the three methods was the use of different portions of the homogenized samples for analysis. In the ideal scenario, PIGE and handheld XRF would analyze the same surface sequentially since both are non-destructive methods; then, the same sample would be sent for analysis by CIC, a destructive method. However, the accelerated timeline of this one-year project necessitated sending one-third of each homogenized sample to each laboratory for simultaneous analysis.

Another limitation of this report is that much of the comparison analysis was performed thus far with the homogenized samples. We will address this limitation in future publications after having finalized a more in-depth data analysis of the results from this study. Although a homogenized sample should provide a better representation of the surfaces of interest, it also requires extensive preparation and destroys the sample. Preparing samples may not be practical during community events, as the ability to preserve intact products and perform quick analyses is one of the main advantages of the handheld XRF.

On the other hand, creating homogenized samples from triplicates of the same product (e.g., three samples of the same jacket), increased our ability to provide meaningful information on the PFAS content of the product. For example, the homogenized samples used in lab analysis were prepared such that only the top surfaces of materials were included—making these results more comparable to XRF and PIGE measurements. Even so, the process of taking samples from the products may have introduced variability in the specific portion of products tested. Although both PIGE and the handheld XRF took measurements in different places to account for this variability, in both intact and homogenized samples, we were unable to confirm whether both laboratories had measured the exact same locations.

Using the handheld XRF as a PFAS screening method

The handheld XRF tested in this study shows promise as a screening method for PFAS in consumer products. As expected, however, the handheld XRF had more difficulty measuring fluorine in low concentrations compared to the lab-based PIGE, which has a more powerful energy beam, deeper penetration depth, and better signal-to-noise detection. Thus, the handheld XRF shows significant promise for screening high fluorine-content products, such as nonstick cookware. The closest alternative, PIGE, has turnarounds of weeks, is 10 to 100 times more expensive than the handheld XRF, and requires a facility that can house a nuclear reactor. Given its portability, real-time information, and lower cost, the handheld XRF potentially fills an important gap by enabling rapid, on-site screening for high-fluorine products where traditional lab methods are impractical, or as a screening tool to prioritize items for further testing when budget and time are limited.

Although XRF results for fluorine concentration across intact and homogenized samples agreed fairly well—supporting use of a portable XRF in the field—the PIGE method showed greater consistency when testing intact versus homogenized samples. Additional analysis comparing intact sample results across methods is planned to build on the findings presented here.

Future studies and refinements

To refine our use of the handheld XRF and understand its capability to predict fluorine concentrations, we are currently conducting a comparison with a high-powered desktop XRF at Purdue University, which will allow us to compare the handheld XRF with a desktop XRF that has greater sensitivity. Another advantage of this ongoing comparison is that we will be able to use the same samples for the comparison and analyze the same surfaces on the items.

Further refinements to the XRF optimization for fluorine detection will involve assessing different materials—some examples include plastics, metal coatings, and textiles. Since

we've only developed a single set of standards based on cellulose laboratory filters, additional work will be needed to assess whether and how XRF measures fluorine in different types of materials since different materials can affect the energy signature detected for fluorine.

Future studies could also determine the depth at which the handheld XRF can measure fluorine in different product matrices with varying densities by creating layered fluorine standards at varying depths. Although preliminary applications of the handheld XRF have reported that the handheld XRF captures photons from a depth of 1 µm (Labquip 2025; Bruker 2025d,e), estimates by our team using the fluorine X-ray mass attenuation coefficients suggest a measurement depth of up to 5 µm for objects with a density of 2 g/cm^3 (NIST 2025).

Additionally, more consideration is needed to establish protocols for deploying the instrument in the field for safe and effective testing at health fairs and other venues where conditions vary. Specifically, the use of a portable, party-sized compressed helium tank is necessary, along with updated software that utilizes external calibrations to estimate concentrations in samples on-site. This software, although expensive (EasyCal, sold by Bruker AXS LLC, costs approximately $5,000), can ostensibly assist with correcting matrix effects using mathematical models. The user, for example, would create a mode (e.g., PFAS carpet mode, PFAS textile mode, PFAS plastic mode, or PFAS pan mode) to be able to measure a specific object for fluorine, ensuring results are much more accurate than those obtained with the generic fluorine calibration derived from fluorine-spiked lab filters used in this study, and allowing for more standardized measurements across staff at community or other events. For example, a plastic mode created beforehand would base its calculation algorithm on calibrants created from dosed plastic material at different levels of fluorine concentration, thereby providing more accurate estimated concentrations and in situ detection ability for plastic products.

At events, due to time constraints, room conditions, and safety concerns, the XRF system will be most useful as a screening tool to identify high, medium, or low levels of fluorine in objects, rather than to provide precise numeric fluorine levels. This information could be used to prioritize further confirmatory analyses.

Understanding PFAS findings in consumer products

Many of the products in our study tested positive for PFAS. Some were not surprising, as they had labels (e.g., "waterproof" or "stainproof") suggesting the use of PFAS, listed PFAS in their ingredients, or had previously tested positive for PFAS. However, some products found to be positive for PFAS were expected to not contain PFAS prior to our testing due to different types of PFAS-free labeling, or findings from earlier tests conducted by different groups (e.g., Mamavation website: https://mamavation.com) and academic publications (e.g., Gluge et al. 2020). Only some of the products identified as potentially not having PFAS

by our testing had labels related to PFAS. For example, a scrub top tested positive for nine PFAS analytes, including PFOA at low, ppb, levels, while exhibiting high total fluorine content across all three analytical methods. This finding contrasts with the company's claim on its website that their products contain "zero PFOA, zero PFOS nor any other harmful chemicals to the environment or to your health."

Products that we initially identified as potentially PFAS-free but later tested positive using at least one of the three methods are concerning and highlight the challenge of identifying safer products —a problem also reported by other authors (Yang et al. 2025). Some labeling is misleading, especially for those listed as PFOA-free, as customers may interpret this as PFAS-free; however, manufacturers may be adding other PFAS instead of PFOA to the product. It was encouraging that products made from materials such as silicone or bamboo mostly had very low or non-detectable levels of PFAS or fluorine in our tests. However, other researchers (Yang et al. 2025) have found PFAS in bamboo straws, suggesting that PFAS-based coatings to protect surfaces may still be used, even if the material itself does not typically contain PFAS.

PFAS in children's products

Childhood, particularly during critical developmental stages, is a sensitive period for exposure to environmental chemicals, including PFAS (Harris et al. 2021). Significant concerns have been raised about PFAS in children's products. The compounds have been detected in newborn babies (Apelberg et al. 2007), and studies have found detectable levels of PFAS (either specific PFAS types or reflected in total fluorine) in a wide range of children's products. For example, both PFAS and PFAS precursors have been detected, with a total fluorine range of 10 to 3,660 ppm, in bedding, clothing, and furnishings commonly used by children and adolescents (Rodgers et al. 2022).

A study on PFAS in the child care environment found that up to 90% of the tested nap mat samples contained up to 21 types of PFAS, with total concentrations ranging from 1.6 to 600 ppb, possibly contributing to PFAS exposure through dust (Zheng et al. 2020). High levels of PFAS or total fluorine have also been detected in bibs, mittens, shoes, stroller covers, diapers, school uniforms, swimsuits, snowsuits, hats, and rain suits (Xia et al. 2022), as well as in car seats (Wu et al. 2021).

Despite the low levels of PFAS found in many of the children's products tested for this study, including many of those reported as concerning in the literature, the highest levels of total fluorine were found in a polyester bib (>710 ppm by CIC, and 448 ppm by PIGE), followed by boots (150 ppm by CIC, and 376 ppm by PIGE) and a board book (32 ppm by CIC, and 126 ppm by PIGE). The handheld XRF detected fluorine in the bib and boot. Our findings of low fluorine content in children's products may reflect manufacturers' shift away from PFAS in response to public pressure and restrictions imposed by several states on specific product categories. Washington, which requires reporting of specific PFAS in children's products,

has been a leader in implementing such restrictions. Washington and other states have also restricted PFAS in a variety of products that overlap with children's products (e.g., food packaging, personal care products and cosmetics, apparel). Such state actions may be encouraging manufacturers to move away from using PFAS in children's products.

PFAS in cosmetics and personal care products

PFAS have been identified in various types of cosmetics and personal care products. In our study, we found high levels of total fluorine in the two eye shadows tested (up to 520 ppm by CIC, and up to 4,875 ppm by PIGE) and in one sample of foundation (440 ppm by CIC, and 36,8027 ppm by PIGE). Differences in total fluorine measured by the different methods may relate to interferences as cosmetics are often complex matrices. PFAS-coated dental floss had the highest PFAS concentrations of a single analyte (N-ethyl perfluorooctanesulfonamidoethanol (NEtFOSE) >>730 ppb,) among all our samples measured by targeted lab analysis. Interestingly, XRF positively detected fluorine in the dental floss, but PIGE did not, and CIC declined to measure it as it was expected to have high levels of fluorine that would risk contaminating the laboratory equipment.

A North America-based research project studied 231 cosmetics purchased from the U.S. or Canada. They noted that high levels of total fluorine were mostly detected in foundations, mascaras, and lip products, with the 6:2 and 8:2 fluorotelomer compounds—which are precursors of perfluoroalkyl carboxylates (PFCAs)—the most commonly detected types of PFAS (ranging from 22–10,500 ppb by product weight) (Whitehead et al. 2021). Similarly, high levels of various PFAS have been detected in items such as eyeliners and eye shadows (Serrano et al. 2021), bronzers, concealers, masks, eye creams, lotions, and primers (Harris et al. 2022), and in personal care products like shampoos, hair oils, moisturizers, cleansers, shaving products, and dental floss (Boronow et al. 2019; Harris et al. 2022).

Notably, PFAS ingredients are rarely listed on cosmetics and personal care products (Harris et al. 2022; Whitehead et al. 2021). Cosmetics and personal care products are typically applied directly to the body, including the skin and mucosa, and many are "leave-on" formulations—such as lotions, moisturizers, sunscreens, and makeup—that remain on the skin for prolonged periods. This prolonged contact increases the potential for dermal absorption and cumulative exposure, particularly when used daily. The lack of ingredient transparency is especially concerning in such contexts, raising concerns about chronic PFAS exposure through routine use of these products.

Washington State law has restricted the use of PFAS in cosmetic products since January 2025 (Washington Department of Ecology 2025a-d). The products we tested were purchased online prior to the effective date of this legislation. Our study results indicate that this product category should continue to be monitored for compliance with the newly enacted legislation.

PFAS in household products

Given that people spend most of their time indoors (up to 80–90%) (Long et al. 2001; Simoni et al. 2003), household products could be one of the main sources contributing to human PFAS exposures. Due to their utility in conveying nonstick, water-, grease-, wrinkle-, and stain-resistant properties, PFAS have been widely used in household products included as additives in materials, such as surface coatings and impregnating agents, lubricants (Fiedler et al. 2010), textile finishing agents (Mumtaz et al. 2019), and paints (Jia et al. 2021).

Among household products we tested, the highest levels of total fluorine were found in PFAS-coated cookware, followed by ski waxes, carpets, artificial turfs, and playground tiles (while artificial turf and playground tiles are not typically considered household items, they were included in this category for this report due to convenience and their relevance to residential settings and consumer exposure.) Nonstick cookware and carpets are two major categories of emerging concern commonly found in homes, as they have been associated with human exposure to PFAS (Ramírez Carnero et al. 2001; Tokranov et al. 2019). This concern is consistent with our findings. Carpets tested in our study measured up to 480 ppm by CIC and up to 170 ppm by PIGE, showing the highest total fluorine with these two methods, while XRF also detected the presence of fluorine. Nonstick cookware measured up to 525,914 ppm by PIGE, but CIC was unable to measure this type of product because the extremely high levels of PFAS risked contaminating the equipment.

Carpets have been identified as a source of PFAS in the indoor environment, and concentrations of certain PFAS have been found to increase significantly after carpet installation (Gewurtz et al. 2009). PFAS-coated nonstick cookware has also been shown to release fumes containing PFAS at normal cooking temperatures (Sajid and Ilyas 2017). Notably, these two product categories can cause repeated and chronic PFAS exposures through ingestion, inhalation, and dermal contact, which could result in bioaccumulation of PFAS in the body and potential long-term health effects. In Washington State, PFAS in carpets has been restricted since January 2025. Given our results suggesting that XRF can detect fluorine in PFAS-treated carpet, the XRF technology may be useful as a tool moving forward that allows for screening products on the market to ensure manufacturers comply with this and other restrictions (Washington Department of Ecology 2025d).

Ski wax was another household product we tested with extremely high levels of PFAS (two of the four ski waxes measured >30,000 ppm by CIC and up to 42,911 by PIGE). The wax was not measured with XRF due to risk of damage to the instrument with sticky substances, which requires removing the protective window for fluorine measurement. Ski wax has been reported in the literature to contain high levels of PFAS (Crawford and Hardman 2024).

We found that the artificial turfs tested had measurable total fluorine concentrations (up to 340 ppm by CIC, and up to 89 ppm by PIGE) while one of the three playground tiles also tested positive for total fluorine (210 ppm by CIC, and 23 ppm by PIGE). These findings align with previous reports that these products are likely to contain PFAS (Gluge et al. 2020). Turf and playground tiles had comparatively lower concentrations compared to PFAS-coated cookware and ski wax.

PFAS in clothing and apparel

PFAS contaminants in clothing and apparel manufacturing have been a global concern (Cousins et al. 2019). Although some companies have committed to eliminating PFAS from their brands (Cousins et al. 2019), both legacy PFAS, such as PFOA and PFOS, and their precursors, like fluorotelomer alcohols (FTOHs), have been detected in clothing textiles in recent studies (Ersdal 2024; Zheng and Salamova 2020). German researchers detected 0.03 to 719 µg/m2 PFAS in all 16 outdoor jackets they tested (Gremmel et al. 2016). They also noted that age, conditions of transport, and storage play a critical role in PFAS concentrations in these textiles, as some PFAS transform into other PFAS structures over time (Dagnino et al. 2016; Gremmel et al. 2016), indicating that exposures are likely ongoing but changing in nature.

Thermoplastic polyurethane elastomer (TPU) (Hassabo et al. 2024) and polytetrafluoroethylene (PTFE) (Newland et al. 2023) are two main groups of chemicals that are used as alternatives to traditionally used PFAS coatings in many consumer products, including clothing textiles. However, both have shown toxic effects based on findings from in vivo and in vitro studies (Campos et al. 2025; Guan et al., 2012).

In our study, we detected extremely high levels of total fluorine in a rain jacket (>30,000 ppm by CIC, and 26,405 ppm by PIGE), as well as relatively high total fluorine in PFAS-coated pants (2,200 ppm by CIC, and 650 ppm by PIGE) and a medical scrub top (870 ppm by CIC, and 226 ppm by PIGE). Encouragingly, the handheld XRF was able to measure the presence of fluorine above 20 ppm in all three products.

PFAS in packaging and containers

We found low levels of total fluorine in most of the packaging and containers tested; however, the highest levels were detected in a bubble gum wrapper (230 ppm by CIC, and <20 ppm by PIGE or handheld XRF). PFAS have been widely added to containers and packaging, including food-contact materials (Seltenrich 2020), due to their water- and oil-resistant performance. Since PFAS can leach (Wang et al. 2024) into food from packaging or containers and enter the human body (Ramírez Carnero et al. 2021), public concerns persist. PFAS have been frequently detected in various types of food-contact materials, such as fast-food containers (Schaider et al. 2017), popcorn bags (Zabaleta et al. 2017), paper plates and cups (Granby and Tesdal Håland 2018), candy wrappers (Chamberlain 2024), and baking paper (Chen et al. 2024). Commonly detected PFAS in food-contact materials include PFOA and other perfluoroalkyl carboxylates (PFCAs), perfluorooctanesulfonic acid (PFOS) and other perfluoroalkyl sulfonates (PFSAs), FTOHs, and polyfluoroalkyl phosphate esters (PAPs) (FDA 2025; Susmann et al. 2019). Schaider et al. employed PIGE to measure total fluorine in around 400 food-contact materials collected from fast-food restaurants across the U.S. They found that 46% of food-contact papers and 20% of paperboard samples had detectable levels of fluorine (Schaider et al. 2017). Since this study was conducted in 2017, PFAS have been regulated or banned in food packaging in many

states (IPEN 2025), including Washington, and as a result, it seems that manufacturers are shifting away from PFAS in paper and paperboard food containers and packaging.

Regulatory and legislative relevance

PFAS in many products in the five categories we studied have been banned or are subject to upcoming bans or reporting requirements under Safer Products for Washington (SPWA) and other state legislation (e.g., Washington Safe Cosmetics Act, Children's Safe Products Act, Washington bans on Aqueous Film Forming Foams (AFFF) and food packaging materials), based on both scientific evidence and Washington State Department of Ecology and Department of Health's engagement with manufacturers and the public (Washington Department of Ecology 2025e). For example, a state law (RCW 70a.222.070) that took effect in 2023 prohibits the manufacturing and sale of certain types of food packaging to which PFAS has been intentionally added (Washington State Legislature. 2025a). A rule (WAC 173-337-110) implementing Cycle 1 of SPWA that went into effect Jan. 2025 restricts PFAS in carpets and rugs and aftermarket stain- and water-resistant treatments (Washington State Legislature 2025c). That same rule will restrict PFAS in leather and textile furniture intended for indoor use beginning in 2026 (reporting of PFAS use has been required by producers, sellers, and distributors of outdoor furniture since 2024). Other pending restrictions from SPWA Cycle 1.5 (which focused specifically on PFAS in consumer products) will restrict PFAS in many types of apparel, cleaning products, and automotive washes beginning in 2027 (Washington Department of Ecology 2025f).

WA state law also includes reporting requirements that address children's products with certain PFAS (Chapter 173-334 WAC) and a pending rule that would address all PFAS in the following product categories beginning in 2027: shoes, apparel for extreme and extended use, automotive waxes, firefighting personal protective equipment, floor waxes and polishes, ski waxes, hard surface sealers, and cookware (DRAFT Chapter 173-337 WAC Safer Products Restrictions and Reporting, Washington Department of Ecology 2025g).

Several other states have also enacted laws restricting or banning PFAS in a growing range of consumer products. State-level actions restricting PFAS use include firefighting foam (15 states), food packaging (12 states), carpets, rugs, and aftermarket treatments (10 states), cosmetics and personal care products (10 states), juvenile products such as car seats and crib mattresses (8 states), menstrual products (7 states), apparel (6 states), cookware (6 states), cleaning products (4 states), and dental floss (4 states) (Safer States 2025). In addition, Maine, Minnesota, and New Mexico have passed legislation that would eventually ban PFAS compounds in nearly all consumer products except for those uses of PFAS that are "currently unavoidable" by 2032 (see, for example, Chapter 60–MN Laws, Minneapolis Legislature 2025). A broad ban on PFAS has been proposed in the European Union and is currently under review by the European Chemicals Agency (ECHA, 2025). As awareness and concerns about PFAS exposures from consumer products increase, so will the demand for regulatory and legislative efforts as well as testing.

Conclusions

The handheld XRF tested in this study can measure total fluorine in various types of consumer products with a wide range of PFAS content, although it performs better for products that have higher fluorine content. The XRF results compare well with those of gold-standard methods, such as total fluorine measurements using PIGE and CIC. We were also able to verify the presence of key PFAS using LC/MS-MS, further confirming the use of fluorine as a tracer for PFAS with handheld XRF.

We found high total fluorine and a number of PFAS compounds in products identified by community members as being of concern, including nonstick cookware, bubble gum wrappers (considered candy wrappers), rain jackets, boots, eye makeup, carpets, and medical scrub top (considered personal protective equipment).

We also found that identifying PFAS-free products was difficult despite numerous publications on the topic and our team's expertise. While many of the products expected not to have PFAS by our team were less likely to test positive for PFAS, that was not always the case. For example, ceramic-coated pans are sold as alternatives for PFAS-coated pans, yet we detected 210 ppm total fluorine with PIGE. The homogenized samples from ceramic pans were powder, and therefore, we do not yet have a reading with the XRF. However, when testing ceramic pans as intact samples (data included in Appendix I), the handheld XRF also measured the presence of fluorine (>20 ppm).

We obtained a statistically significant calibration curve using NaF-spiked filters. Although we were able to estimate a detection limit of 20 ppm for fluorine based on calculations, further refinements are needed to enable accurate measurement of fluorine using handheld XRF at such low levels. Additional testing would be necessary to deploy the instrument for easy use in the field for quantitative purposes (i.e., numerical results). Specifically, tailored calibrations and refinements of the mathematical algorithms are required to correct for background and matrix effects in situ. There is also a need for further sample preparation and testing for the analysis of powders, gels, creams, and other materials that could damage the exposed detector.

Despite the need for continued method development, handheld XRF shows strong promise as a screening tool, especially for high-PFAS objects that are often not amenable to analysis with CIC and are of the greatest concern to communities.

We recommend that the handheld XRF be used for:

- A screening tool to identify objects that contain high concentrations of fluorine (PFAS).
- A method to ground-truth the effectiveness of Washington's existing restrictions on PFAS in products.
- A tool to help government agencies and Washington residents identify products to avoid and safer products to purchase.
- A tool for government agencies to prioritize products for further quantitative and analytical testing as candidates for state restrictions through Safer Products for Washington or other legislation, and to determine when PFAS-free replacements may exist that should be further examined.
- An instrument for agencies to screen items that might be considered dangerous waste.

We recommend that the handheld XRF be further developed for use in:

- Measuring fluorine in products that have low to moderate levels of PFAS by tailoring calibrations and corrections for their specific materials. Because of this, all sample analyses in this report that rely on XRF-based fluorine concentration estimates should be considered preliminary and subject to future adjustments.
- Testing the handheld XRF in the field using a party-sized portable helium tank and adding software to display estimated fluorine concentrations on the instrument screen.

We recommend the following next steps for our work and that of collaborators and state programs focused on PFAS:

- Test more products in the future. Priority categories recommended for further testing include food-contact materials, children's products, carpets, turf, and other play surfaces. We tested a limited number of cosmetics and packaging in our study; a more comprehensive exploration of PFAS in these product categories is warranted. Specifically for cookware, and considering these products were within products of greatest concern to poll participants, we recommend expanding the types and brands of cookware tested to inform relevant regulations and local replacement efforts.
- Further develop XRF reading thresholds (through additional testing) for messaging during public events or as screening parameters that indicate when a product is unlikely, may be likely, or highly likely to have PFAS.
- Further engage communities through health fairs and other venues. The handheld XRF could be particularly useful for screening for high-fluorine content in cookware and other nonstick kitchen and food-contact materials.
- Further testing by material types to determine the likelihood of finding PFAS based on the material of the products. This approach could help identify materials and products for further exploration as "safer options."

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Appendices

Appendix I: List of products and surfaces analyzed for PFAS and analysis results by LC-MS/MS, CIC, PIGE, and handheld XRF

Table I-1. Samples of children's products (n = 40)

Sample Description	PFAS-Suspected§	# PFAS Detected by LC-MS/MS	Most Abundant PFAS Detected*	CIC (ppm)	PIGE (ppm)		Handheld XRF (ppm)	
				Homogenized	Intact	Homogenized	Intact	Homogenized
Pacifier 1 (rubber nipple)	No	0		0.4	0	<= 20	> 20	> 20
Pacifier 1 (plastic mouth shield)	Yes	1	PFBS (9.4 ppb)	< 1.3	Not tested	<= 20	Not tested	<= 20
Pacifier 2 (silicone nipple)	No	0		6.8	Not tested	<= 20	<= 20	> 20
Pacifier 2 (plastic mouth shield)	Yes	0		0.4	Not tested	<= 20	<= 20	<= 20
Pacifier 3 (silicone body)	No	0		< 1.8	Not tested	<= 20	<= 20	<= 20
Pacifier clip 1 (linen strap)	Yes	0		6.5	Not tested	<= 20	<= 20	<= 20
Pacifier clip 2 (silicone beads cord)	No	0		4.9	Not tested	<= 20	<= 20	<= 20
Bib 1 (polyester body)	Yes	8	PFBS (1.5 ppb); PFOA (1.3 ppb); PFDA (< 0.78 ppb)	> 710	Not tested	448	> 20	> 20
Bib 2 (PEVA body)	Yes	0		Not detected	Not tested	<= 20	<= 20	<= 20
Bib 3 (silicone body)	No	0		4.2	13	<= 20	> 20	> 20
Kid's bowl 1 (plastic bowl)	Yes	0		4	Not tested	<= 20	Not tested	<= 20
Kid's bowl 1 (silicone suction base)	No	0		2.6	Not tested	<= 20	<= 20	<= 20
Kid's bowl 2 (bamboo bowl)	No	1	PFBS (< 0.98 ppb)	2.8	Not tested	<= 20	<= 20	Not tested
Kid's bowl 2 (silicone suction base)	No	0		4.8	3	<= 20	> 20	<= 20

Kid’s sippy cup (silicone spout)	No	0		2.3	Not tested	<= 20	<= 20	<= 20
Kid’s sippy cup (plastic body)	Yes	0		2.3	Not tested	<= 20	<= 20	<= 20
Baby bottle (nipple)	No	0		2.5	Not tested	<= 20	> 20	<= 20
Baby bottle (silicone body)	No	0		2.4	Not tested	<= 20	> 20	<= 20
Diaper 1(direct contact cotton surface)	Yes	1	PFBS (< 0.83 ppb)	2.2	Not tested	<= 20	<= 20	<= 20
Diaper 2 (direct contact cotton surface)	Yes	1	PFBS (< 0.99 ppb)	1.7	Not tested	<= 20	<= 20	<= 20
Baby waterproof rain jacket (outer nylon shell)	Yes	9	PFHxA (1.8 ppb); NMeFOSE (1.3 ppb); PFOA (1.1 ppb)	15	7	<= 20	<= 20	<= 20
Boys’ waterproof jacket (outer nylon shell)	Yes	0		3.2	Not tested	<= 20	> 20	<= 20
Baby boots (outer fabric surface)	Yes	2	PFBS (< 0.9 ppb); PFOA (< 0.9 ppb)	150	581	376	> 20	> 20
Baby boots (inner fur)	No	0		6.5	1	<= 20	> 20	> 20
Kid’s bandage 1 (strip)	Yes	2	NMeFOSE (1.5 ppb); PFBS (1.2 ppb)	5.1	Not tested	<= 20	<= 20	<= 20
Kid’s bandage 2 (strip)	Yes	1	PFBS (2.5 ppb)	7.1	Not tested	<= 20	> 20	<= 20
Kid’s bandage 3 (strip)	Yes	1	PFBS (< 0.82 ppb)	0.74	Not tested	<= 20	<= 20	<= 20

Car seat 1 (head rest)	No	2	NMeFOSE (1.9 ppb); PFOS (< 0.92 ppb)	2	Not tested	<= 20	<= 20	> 20
Car seat 2 (head rest)	Yes	1	PFBS (< 0.88 ppb)	1.1	Not tested	<= 20	> 20	> 20
Stuffed elephant toy (outer fabric)	Yes	1	PFBS (< 0.93 ppb)	0.69	Not tested	<= 20	<= 20	<= 20
Maracas toy (fabric pom-pom)	Yes	1	PFOA (< 0.98 ppb)	5.5	Not tested	<= 20	> 20	<= 20
Maracas toy (plastic handle)	Yes	0		2.3	Not tested	<= 20	<= 20	<= 20
Children’s book (paper)	Yes	4	NMeFOSE (2.6 ppb); PFOA (< 0.97 ppb); PFPeA (< 0.97 ppb)	14	1	<= 20	> 20	<= 20
Children’s board book	Yes	12	PFNA (1.5 ppb); PFBA (< 2.3 ppb); PFPeA (1.2 ppb)	32	Not tested	126	<= 20	<= 20
Crib mattress protector 1 (outer waterproof layer)	Yes	1	PFBS (< 0.87 ppb)	2.6	Not tested	<= 20	> 20	<= 20
Crib mattress protector 2 (outer waterproof layer)	Yes	1	PFBS (3.1 ppb)	0.92	Not tested	<= 20	> 20	<= 20
Kid’s backpack (outer water-resistant surface)	Yes	1	PFBS (< 0.86 ppb)	1.9	Not tested	<= 20	> 20	<= 20
Waterproof playard sheet (cotton-polyester blend)	Yes	1	PFBS (5.1 ppb)	0.6	Not tested	<= 20	<= 20	<= 20
Toddler swim hat (polyester)	Yes	1	PFBS (< 0.88 ppb)	5.8	Not tested	<= 20	<= 20	<= 20

Reusable snack bag (polyester with embedded TPU for waterproofing)	Yes	0		3.7	Not tested	<= 20	> 20	> 20

**See full name of individual PFAS and their abbreviations in Appendix IV below.*

§ "PFAS-Suspected" indicates a pre-analysis hypothesis based on product claims, labeling, materials, or other publicly available information prior to any fluorine or PFAS testing. We defaulted to assuming PFAS presence when information was unclear.

Table I-2. Samples of cosmetics and personal care products (n = 10)

Sample Description	PFAS-Suspected§	# PFAS Detected by LC-MS/MS	Most Abundant PFAS Detected*	CIC (ppm)	PIGE (ppm)		Handheld XRF (ppm)	
				Homogenized	Intact	Homogenized	Intact	Homogenized
Dental floss 1 (PTFE-based)	Yes	1	NEtFOSE (730* ppb)	Not tested	Not tested	<= 20	> 20	> 20
Dental floss 2 (non PTFE-based)	No	0		6	Not tested	<= 20	<= 20	<= 20
Body deodorant 1	Yes	0		3.1	Not tested	<= 20	Not tested	Not tested
Body deodorant 2	No	1	NMeFOSE (1.1 ppb)	Not detected	Not tested	<= 20	Not tested	Not tested
Eye shadow 1	Yes	0		520*	Not tested	4,875	Not tested	Not tested
Eye shadow 2	No	0		420*	Not tested	252	Not tested	Not tested
Lip stick 1	Yes	0		85	Not tested	<= 20	Not tested	Not tested
Lip stick 2	No	0		43	Not tested	<= 20	Not tested	Not tested
Sunscreen stick SPF 50	No	0		58	Not tested	<= 20	Not tested	Not tested
Powder foundation, SPF 15	Yes	0		440*	Not tested	368,027†	Not tested	Not tested

** Result exceeded calibration range and the concentration is an approximate value.*

† Result exceeded PIGE's highest standard and the reported concentration is an approximate value.

¶ See full name of individual PFAS and their abbreviations in Appendix IV below.

§ "PFAS-Suspected" indicates a pre-analysis hypothesis based on product claims, labeling, materials, or other publicly available information prior to any fluorine or PFAS testing. We defaulted to assuming PFAS presence when information was unclear.

Table I-3. Samples of household products (n = 35)

Sample Description	PFAS-Suspected§	# PFAS Detected by LC-MS/MS	Most Abundant PFAS Detected*	CIC (ppm)	PIGE (ppm)		Handheld XRF (ppm)	
				Homogenized	Intact	Homogenized	Intact	Homogenized
Carpet 1	Yes	6	PFHxA (< 1.1 ppb); PFBS (< 1.1 ppb); PFOS (< 1.1 ppb)	480*	Not tested	61	<= 20	<= 20
Carpet 2	Yes	3	NEtFOSE (1.1 ppb); PFHxA (< 1.1 ppb); PFPeA (< 1.1 ppb)	480*	Not tested	170	> 20	> 20
Carpet 3	No	1	NMeFOSE (< 0.97 ppb)	8.8	Not tested	<= 20	> 20	> 20
Carpet 4	No	0		19	Not tested	<= 20	<= 20	<= 20
Playground tile 1	Yes	0		76	Not tested	26	<= 20	> 20
Playground tile 2	Yes	0		210	Not tested	23	<= 20	<= 20
Playground tile 3	Yes	1	NMeFOSE (< 1 ppb)	57	Not tested	<= 20	<= 20	> 20
Playground tile 4	Yes	0		51	209	26	<= 20	<= 20
Artificial turf 1	Yes	0		340*	Not tested	89	<= 20	<= 20
Artificial turf 2	Yes	1	PFOA (< 0.87 ppb)	220	412	64	<= 20	<= 20
Artificial turf 3	No	0		16	Not tested	<= 20	<= 20	<= 20
Artificial turf 4	No	0		180	Not tested	<= 20	<= 20	<= 20

Artificial turf 5	No	0		85	87	<= 20	<= 20	<= 20
Ski wax 1 (fluorinated)	Yes	15	PFDA (710 ppb); PFNA (360 ppb); PFDoA (240 ppb)	Not tested	Not tested	42,911†	Not tested	Not tested
Ski wax 2 (fluorinated)	Yes	11	NEtFOSE (280 ppb); PFOA (13 ppb); PFHpA (2.4 ppb)	> 30,000*	Not tested	2,774	Not tested	Not tested
Ski wax 3 (non-fluorinated)	No	1	PFTeA (< 1.1 ppb)	6.6	Not tested	<= 20	Not tested	Not tested
Ski wax 4 (non-fluorinated)	No	5	PFDA (1.6 ppb); PFTeA (1.3 ppb); PFDoA (1.2 ppb)	7.1	Not tested	<= 20	Not tested	Not tested
Nonstick fry pan (PTFE-coated) 1	Yes	0		Not tested	Not tested	172,320 †	> 20	Not tested
Nonstick fry pan (PTFE-coated) 2	Yes	11	PFOA (5.2 ppb); PFBA (4.4 ppb); PFPeA (1.3 ppb)	Not tested	Not tested	97,273†	> 20	Not tested
Nonstick fry pan (PTFE-coated) 3	Yes	11	PFBA (< 4.3 ppb); PFOA (< 1.7 ppb); PFHxA (< 1.7 ppb)	Not tested	Not tested	142,751 †	> 20	Not tested
Nonstick fry pan (PTFE-coated) 4	Yes	14	PFBA (12 ppb); PFPeA (9.9 ppb); PFHxA (8.7 ppb)	Not tested	Not tested	525,914 †	> 20	Not tested

Nonstick stock pot (PTFE-coated)	Yes	13	PFBA (< 5 ppb); PFBS (2.6 ppb); PFPeA (2.4 ppb)	Not tested	Not tested	182,843 †	> 20	Not tested
Rice cooker (nonstick PTFE-coated removable pot)	Yes	0		Not tested	Not tested	38	<= 20	Not tested
Nonstick loaf pan (PTFE-coated)	Yes	11	PFBA (< 5.3 ppb); PFPeA (< 2.1 ppb); FOSA (< 2.1 ppb)	Not tested	Not tested	97,273†	> 20	Not tested
Air fryer (PTFE-coated)	Yes	5	PFBA (< 2.6 ppb); PFPeA (< 1 ppb); PFHxA (< 1 ppb)	Not tested	Not tested	201,818 †	> 20	Not tested
Sandwich maker (PTFE-coated)	Yes	7	PFOA (< 2.1 ppb); PFNA (< 2.1 ppb); PFPeA (< 2.1 ppb)	Not tested	Not tested	245,467 †	> 20	Not tested
Fry pan (cast-iron)	No	1	PFBS (< 0.92 ppb)	Not tested	Not tested	<= 20	<= 20	Not tested
Nonstick fry pan (ceramic-coated) 1	No	0		Not tested	Not tested	<= 20	<= 20	Not tested
Nonstick fry pan (ceramic-coated) 2	No	3	PFOS (8.7 ppb); 6:2 FTS (< 1.1 ppb); 8:2 FTS (< 1.1 ppb)	Not tested	Not tested	81	<= 20	Not tested
Nonstick fry pan (ceramic-coated) 3	No	0		Not tested	Not tested	210	> 20	Not tested
Dutch oven pot (cast iron)[#]	No	1	PFBA (< 1 ppb)	Not tested	16,802.5	Not tested	> 20	Not tested

Rice cooker (stainless steel removable pot)[#]	No	0		Not tested	25.7	Not tested	> 20	Not tested
Nonstick loaf pan (ceramic-coated)	No	0		Not tested	Not tested	<= 20	<= 20	Not tested
Air fryer (ceramic-coated)	No	0		Not tested	Not tested	302	<= 20	Not tested
Sandwich maker (ceramic-coated)	No	3	6:2 FTS (< 0.97 ppb); PFOA (< 0.97 ppb); FOSA (< 0.97 ppb)	Not tested	Not tested	<= 20	> 20	Not tested

** Result exceeded calibration range and the concentration is an approximate value.*

† Result exceeded PIGE's highest standard and the reported concentration is an approximate value.

¶ See full name of individual PFAS and their abbreviations in Appendix IV below.

§ "PFAS-Suspected" indicates a pre-analysis hypothesis based on product claims, labeling, materials, or other publicly available information prior to any fluorine or PFAS testing. We defaulted to assuming PFAS presence when information was unclear.

 # Samples were wiped prior to targeted PFAS analysis, as samples could not be homogenized due to matrix-related challenges.

Table I-4. Samples of clothing and apparel (n = 5)

Sample Description	PFAS-Suspected§	# PFAS Detected by LC-MS/MS	Most Abundant PFAS Detected*	CIC (ppm)	PIGE (ppm)		Handheld XRF (ppm)	
				Homogenized	Intact	Homogenized	Intact	Homogenized
Pant (PFAS finish)	Yes	12	PFOA (25 ppb); PFHxA (17 ppb); PFDA (11 ppb)	2,200*	Not tested	650	> 20	> 20
Women's leggings	Yes	4	NEtFOSE (1.4 ppb); PFOA (1.2 ppb); PFOS (< 0.96 ppb)	11	Not tested	<= 20	> 20	<= 20
Men's rain jacket (nylon) 1	Yes	15	PFBS (610* ppb); NMeFOSE (270* ppb); PFBA (180* ppb)	> 30,000*	Not tested	26,405†	> 20	> 20
Men's rain jacket (nylon) 2	No	0		11	Not tested	<= 20	<= 20	<= 20
Scrub top	No	9	PFOA (26 ppb); PFDA (11 ppb); PFDoA (4.5 ppb)	870*	Not tested	226	> 20	> 20

** Result exceeded calibration range and the concentration is an approximate value.*

† Result exceeded PIGE's highest standard and the reported concentration is an approximate value.

¶ See full name of individual PFAS and their abbreviations in Appendix IV below.

§ "PFAS-Suspected" indicates a pre-analysis hypothesis based on product claims, labeling, materials, or other publicly available information prior to any fluorine or PFAS testing. We defaulted to assuming PFAS presence when information was unclear.

Table I-5. Samples of packaging and containers (n = 10)

Sample Description	PFAS-Suspected§	# PFAS Detected by LC-MS/MS	Most Abundant PFAS Detected*	CIC (ppm)	PIGE (ppm)		Handheld XRF (ppm)	
				Homogenized	Intact	Homogenized	Intact	Homogenized
Nonstick parchment paper	Yes	1	PFBS (< 0.96 ppb)	11	Not tested	<= 20	<= 20	<= 20
Plastic sandwich bag 1	No	0		9	Not tested	<= 20	<= 20	<= 20
Plastic sandwich bag 2	Yes	0		8.8	Not tested	<= 20	<= 20	<= 20
Disposable plastic cup	Yes	0		5.2	Not tested	<= 20	<= 20	<= 20
Disposable paper cup	No	0		78	Not tested	<= 20	<= 20	<= 20
To-go box (plastic)	Yes	4	7:3 FTCA (< 0.94 ppb); NEtFOSAA (< 0.94 ppb); NEtFOSE (< 0.94 ppb)	8.9	Not tested	<= 20	<= 20	<= 20
To-go box (paper with poly-coated interior)	Yes	0		8.2	Not tested	<= 20	<= 20	<= 20
Bubble gum wrapper	Yes	0		230	Not tested	<= 20	<= 20	<= 20
Peanut butter cup	Yes	1	NEtFOSE (1 ppb)	20	Not tested	<= 20	> 20	<= 20
Microwave popcorn bag	Yes	0		9.9	Not tested	<= 20	<= 20	Not tested

* *See full name of individual PFAS and their abbreviations in Appendix IV below.*

§ "PFAS-Suspected" indicates a pre-analysis hypothesis based on product claims, labeling, materials, or other publicly available information prior to any fluorine or PFAS testing. We defaulted to assuming PFAS presence when information was unclear.

Appendix II: Handheld XRF fluorine optimization

This section describes our approach to optimizing key XRF settings—voltage, current, and scan duration—to enhance the instrument's sensitivity and specificity for fluorine detection. We also tested baseline performance to detect fluorine using products with known PFAS content and confirmed the absence of fluorine signals in negative controls. The goal was to establish a scan configuration that maximizes the ability to detect fluorine.

Establishing XRF baseline performance

The first step toward optimizing our XRF settings was to establish baseline performance of the instrument by scanning consumer products with confirmed PFAS content (i.e., positive controls) and those without PFAS (i.e., negative controls). Scans of positive controls (e.g., PFAS-coated pan) were done to confirm the ability of the instrument to detect fluorine and to characterize fluorine signals within the XRF spectrum, including at which energy channel the fluorine peak occurs. Scans of negative controls (e.g., microscope slide) were used to confirm the absence of fluorine signal and characterize baseline negative signal (or "noise") within the XRF spectrum in PFAS-free products. All scans to establish baseline performance were completed using settings initially hypothesized to maximize the detected radiation intensity (measured as "counts" of X-ray photons detected over the course of the scan): Voltage - 15 kV; Current - 200 μA; Duration - 10 min; Atmosphere - Helium flush; Filters – none; no detector protective window.

XRF instrument setting optimization

Voltage (kV) optimization: We identified the optimal voltage setting, which is the excitation energy used to stimulate the emission of X-rays and is measured in kilovolts (kV). The voltage determines the energy of the X-rays, thus directly affecting the resulting XRF spectrum. Our goal was to identify the voltage setting that maximized the signal-to-noise ratio (see below) for fluorine while minimizing the instrument's dead time (i.e., the time in which the detector cannot detect X-rays because it is overloaded, expressed as a percentage). Minimizing dead time is important because high dead time reduces the detector's ability to register incoming photons and can distort quantification.

Signal-to-noise calculations involved measurements at various voltage settings from several positive ("signal") and negative ("noise") controls representing a variety of matrices. All samples were scanned at 10 – 15 kV voltage settings, with all other parameters held constant (Current - 200 μA; Duration - 10 min; Atmosphere - Helium flush; Filters – none; No window). We also evaluated lower kV settings, but there was a substantial reduction in signal below 10 kV. We calculated a metric using paired measurements from positive and negative controls to assess signal-to-noise performance at each voltage. The data used in the calculations were the sum of X-ray counts within the fluorine peak region (0.64–0.68 keV) for each sample. For each positive-negative pair, we computed the signal-to-noise metric as the square root of negative control counts divided by the positive control counts, as shown below, with lower values representing better performance. Each positive and negative control was compared, resulting in six calculations.

Equation 1

$$SNR\ Metric\ =\ \frac{\sqrt{Counts_{Noise}}}{Counts_{Signal}}$$

Current (μA) optimization: After identifying the optimal voltage setting, we set the current setting, which refers to the flow of electrons within the X-ray tube (measured in microamperes, μA) and affects the number of X-rays produced per second. Our goal was to maximize current—which can boost signal intensity to improve detection of weak signals—without exceeding instrument or safety limits (Bruker 2025c). To avoid exceeding safe operating limits for the X-ray tube, we used manufacturer guidance to determine the upper bound of allowable current at our selected voltage, applying linear interpolation.

Scan duration optimization: While a 10-minute duration was used for scans associated with optimizing the XRF parameters, we subsequently evaluated whether a shorter, 5-minute duration allowed for adequate detection in order to reduce overall time for data collection. We compared estimated limits of detection or LODs from calibration curves using spiked samples (see below) at both 5- and 10-minute durations to ensure the shorter scan time was adequate. Further optimization is needed to assess whether the scan duration time can be lowered even further while maintaining ability to detect fluorine.

Appendix III: Handheld XRF fluorine calibration and quantitation

Handheld XRF fluorine calibration

We conducted a calibration to establish the relationship between the XRF signal (counts) and known fluorine concentration. As standards, we used laboratory filters spiked with 100 μL of known concentrations of fluorine ranging from 50 ppm to 10,000 ppm. These concentrations cover the wide range of fluorine levels expected in different consumer products, including those with very low or very high levels. The eight concentrations—50, 100, 200, 500, 1,000, 2,000, 5,000, and 10,000 ppm—were spaced to give a good spread across the range and to allow us to check that the XRF gave consistent and accurate results. The fluorine standard was an aqueous solution of sodium fluoride (NaF) (Fluoride Standard Solution Traceable to SRM from NIST NaF in H2O 10,000 mg/L, Ricca Catalog 3174.10-16 Lot 150K43), which was spiked on Methylethyl cellulose (MCE) filters (SKC 225-5 37 mm, 0.8 um pore size Lot MO028845).

We tested each of these concentrations using one spiked filter per level, measured at least 3 times in the same place. Each standard filter was scanned at least three times using the optimized XRF settings (Voltage: 12 kV; Current: 175 μA; Duration: 5 min; Helium atmosphere; No filters; No window). The raw spectrum data were then extracted for analysis. The primary metric used in the calibration process was the sum of X-ray counts within the fluorine peak region (0.64–0.68 keV). Counts for each concentration were plotted and fit with both linear and logarithmic models to characterize the nature and strength of the relationship.

The QA/QC procedures include several steps to ensure reliable measurements. First, the XRF analyzer was turned on and allowed to warm up for 5 minutes before any measurements were taken. A Bruker check sample (solder check, plastic check, or silver round) is then selected and measured three times without helium; if any measurement fell outside the reference range, an additional scan was performed, and the average of all runs is calculated. Our protocol included a process in which, had the average remained out of range, testing would have been paused for troubleshooting, although this never occurred. Afterward, helium is connected, and the chamber is flushed for 5 minutes to prepare for fluorine-specific QC checks. One positive and one negative control sample were tested, and their spectra were compared to historical runs for consistency in peak positions and intensity. Validation steps were done in consultation with the team to assess the need to re-run samples, but none were needed. During scanning of the product samples, replicate testing was conducted to assess instrument reproducibility by selecting approximately 5% of samples per matrix for duplicate testing at the same spot, and to evaluate surface variability by testing approximately 5% of samples at two to three different spots. Some of the prepared homogenized samples that had two types of surfaces, both ends of the microscope slide were tested. Finally, sensitivity evaluations using calibration curves were performed.

QC Reference Materials included positive controls [i.e., PFAS-QC-POSITIVE-1: 1 mil PFA film (transparent); PFAS-QC-POSITIVE-2: PTFE film; PFAS-QC-POSITIVE-3: PTFE tape] and negative controls [i.e., PFAS-QC-NEGATIVE-1: Ziploc bag (2-gallon size); PFAS-QC-NEGATIVE-2: Blank mixed cellulose ester (MCE) filter; PFAS-QC-NEGATIVE-3: microscope slide].

Handheld XRF fluorine quantitation

To evaluate how well the XRF performs and to compare different ways of measuring fluorine, we developed a method to convert XRF data into an estimated fluorine concentration for each sample. This process involved creating a calibration curve, which is a mathematical equation that shows the connection between the XRF signal (the total number of X-ray counts detected in the energy range where fluorine appears) and fluorine concentration (measured in parts per million, or ppm).

For the calibration, we used reference materials with known fluorine concentrations ranging from 50 to 10,000 ppm. This step helped confirm that the instrument was working correctly across different concentration levels.

The minimum detection limit (MDL) was calculated from the measurements of the spiked filters of varying concentrations of fluorine. We used a calibration line function to determine the minimum detectable limit (MDL) as twice the square root of the background counts, which provides a standard error for our measurement. The counts from the device in the fluorine region, when we know there is no fluorine present in our sample, are defined as the background counts. Then, we divide that number by the slope of a linear fit

of the calibration data, which would give us counts per known concentration unit increase. The sum of the total counts refers to the region of interest (ROI) within the energy spectrum that is relevant to the fluorine signal, and the slope was taken as a linear approximation from our full calibration standard set made of NaF. Specifically, using the ROI of 0.64–0.68 keV, the estimated MDL was 24 ppm for King County's handheld XRF and 21 ppm for the University of Washington's handheld XRF.

Next, we examined multiple ways to define the mathematical relationship between the XRF signal and fluorine concentration. We tried different types of models (such as linear and logarithmic equations), explored various energy ranges within the XRF spectrum, and considered different techniques for adjusting results based on the sample's composition.

Based on our initial findings, we selected a logarithmic model, focused on the 0.64–0.68 keV energy region, and applied a correction for total X-ray counts to improve accuracy. This model was used to estimate fluorine concentrations for all XRF measurements. This model was then applied to all XRF measurements, allowing us to estimate fluorine concentrations in each sample based on the recorded XRF signal.

It is important to note that our results suggest that further refinement is needed to improve XRF-based fluorine concentration estimates. Additional reference materials with different sample compositions will need to be tested and compared to enhance accuracy. Because of this, all sample analyses in this report that rely on XRF-based fluorine concentration estimates should be considered preliminary and subject to future adjustments.

To address this limitation, we are exploring alternative analytical approaches that do not depend on individual concentration estimates. These include methods that assess trends in concentration rankings and techniques that distinguish between detected and non-detected fluorine levels. These approaches help ensure that meaningful insights can still be drawn, even as refinements to XRF-based estimates continue.

Appendix IV: List of 40 PFAS analyzed by LC/MS-MS*

PFAS chemical names (Abbreviation)
Perfluorobutanoic acid (PFBA)
Perfluoropentanoic acid (PFPeA)
Perfluorohexanoic acid (PFHxA)
Perfluoroheptanoic acid (PFHpA)
Perfluorooctanoic acid (PFOA)
Perfluorononanoic acid (PFNA)
Perfluorodecanoic acid (PFDA)
Perfluoroundecanoic acid (PFUnA)
Perfluorododecanoic acid (PFDoA)
Perfluorotridecanoic acid (PFTrDA)
Perfluorotetradecanoic acid (PFTeA)
Perfluorobutanesulfonic acid (PFBS)
Perfluoropentanesulfonic acid (PFPeS)
Perfluorohexanesulfonic acid (PFHxS)
Perfluoroheptanesulfonic acid (PFHpS)
Perfluorooctanesulfonic acid (PFOS)
Perfluorononanesulfonic acid (PFNS)
Perfluorodecanesulfonic acid (PFDS)
Perfluorododecanesulfonic acid (PFDoS)
Perfluorooctanesulfonamide (FOSA)
N-methyl perfluorooctanesulfonamidoacetic acid (NMeFOSAA)
N-ethyl perfluorooctanesulfonamidoacetic acid (NEtFOSAA)
1H,1H, 2H, 2H-Perfluorohexane sulfonic acid (4:2 FTS)
1H,1H, 2H, 2H-Perfluorooctane sulfonic acid (6:2 FTS)
1H,1H, 2H, 2H-Perfluorodecane sulfonic acid (8:2 FTS)
N-ethyl perfluorooctanesulfonamide (NEtFOSA)
N-methyl perfluorooctanesulfonamide (NMeFOSA)
N-methyl perfluorooctanesulfonamidoethanol (NMeFOSE)
N-ethyl perfluorooctanesulfonamidoethanol (NEtFOSE)
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid (9Cl-PF3ONS)

*All the PFAS tested using EPA method 1633.

Hexafluoropropylene oxide dimer acid (HFPO-DA/GenX)
11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid (11Cl-PF3OUdS)
4,8-Dioxa-3H-perfluorononanoic acid (ADONA)
3-Perfluoropropyl propanoic acid (3:3 FTCA)
2H,2H,3H,3H-Perfluorooctanoic acid (5:3 FTCA)
3-Perfluoroheptyl propanoic acid (7:3 FTCA)
Nonafluoro-3,6-dioxaheptanoic acid (NFDHA)
Perfluoro-4-methoxybutanoic acid (PFMBA)
Perfluoro-3-methoxypropanoic acid (PFMPA)
Perfluoro (2-ethoxyethane) sulfonic acid (PFEESA)

Appendix V: Figures and corresponding alt (alternative) text descriptions

Figure 1: Ranking of products for PFAS testing within five key categories.

This bar chart shows the number of participants (out of 44) who prioritized different consumer products for PFAS testing across five categories. In the "Children" category, feeding utensils and pacifiers received the most votes. In "Clothing," jackets and menstrual underwear were top priorities. In "Cosmetics," lipstick and sunscreen stick were ranked highest. For "Household" products, nonstick cookware and carpet received the most attention. Within "Packaging," fast food wrappers were most frequently selected, while fluorinated HDPE containers received the fewest votes overall. The chart reflects combined input from all participants.

Figure 2: Ranking of products for PFAS testing by respondent category.

This bar chart compares how two stakeholder groups (Community Partners and Government/ Academia) ranked various consumer products for PFAS testing across five categories: Children, Clothing, Cosmetics, Household, and Packaging. Each product is accompanied by horizontal bars showing the number of votes it received from each group. Community partners generally provided more votes across most product categories, with particularly high interest in items like pacifiers, jackets, nonstick cookware, and fast food wrappers. In contrast, government and academic respondents gave fewer votes overall but showed relatively higher prioritization for some cosmetics, such as lipstick. The chart highlights differences in priorities that may reflect varying levels of exposure awareness, research focus, or product usage across stakeholder groups.

Figure 3. Choosing products and surfaces for testing.

This diagram shows five prioritized product categories selected for PFAS testing: Children's products, Cosmetics & personal care, Household products, Clothing, and Packaging. Each category is illustrated with an icon (e.g., baby bib for children's products, dental floss for cosmetics). Below each category, two test types are represented by colored circles: intact surface (solid color) and homogenized material (patterned). The legend at the bottom explains these test types. This figure visually summarizes the approach to sampling PFAS by testing both whole surfaces and ground-up material across key consumer product categories.

Figure 4. Schematic of preparation of "homogenized" samples for products with one or more surfaces for PFAS testing with the handheld XRF using microscope slides.

This diagram illustrates how products, such as a bib and a baby bottle, were prepared and tested for fluorine. For each item, two types of samples were collected: intact surface samples (shown as solid-colored circles), which represent unaltered portions of the product, and homogenized samples (patterned circles), which involve grinding a small portion of the product into fine particles. The homogenized material was then mounted onto double-sided tape affixed to a microscope slide for analysis.

Figure 5. Photos of prepared slides with taped, "homogenized" samples of: a) nylon jacket, showing two distinguishable surface types; b) adhesive bandage, showing only one surface type; c) playground tile made of rubber, showing only one surface type; and d) artificial turf, showing two distinguishable surface types.

This figure shows photographs of prepared microscope slides with homogenized product samples affixed to double-sided tape. Each slide displays distinct surface types from different consumer products. (a) nylon jacket is shown with two visibly different surface textures. (b) An adhesive bandage is shown with one consistent surface type. (c) A playground tile made of rubber is prepared similarly with a single surface type. (d) An artificial turf sample is shown with two distinguishable surface types, demonstrating the variation in material that can exist within a single product. These examples illustrate how samples were prepared for fluorine analysis using the handheld XRF.

Figure 6. Different methods and laboratories for testing products for PFAS for the optimization of the handheld XRF.

This diagram displays three laboratories and analytical methods used to test products for PFAS. The first panel shows a handheld XRF instrument at the University of Washington lab, capable of testing both intact surfaces and homogenized samples (photo of tabletop XRF setup by S. Fish). The second panel depicts PIGE testing at Forever Analytical Lab using a 3 MV Tandem Pelletron Accelerator, which also tests both sample types. The third panel features the Eurofins laboratory, where homogenized samples were analyzed using CIC and LC/MS/MS; only homogenized samples were tested here. Each panel includes icons indicating the sample types tested and a photo of the equipment used.

Figure 7. Testing products for PFAS set up with handheld XRF.

This diagram shows the setup for fluorine testing using a handheld XRF analyzer. The XRF device is positioned over a frying pan sample, with connections to a laptop used for remote control and data analysis, a helium gas tank for purging, and a flow meter to regulate gas flow.

Figure 8. XRF spectrum from different objects known not to contain fluorine (left, negative controls) and known to contain fluorine (right, positive controls).

This figure shows two graphs comparing fluorine signals detected by XRF in different materials. The y-axis represents signal strength on a log scale, and the x-axis shows energy levels (in keV), focusing on the fluorine detection region between 0.5 and 0.8 keV. The left graph shows results from negative controls, which are materials not expected to contain fluorine. These items include a 2-gallon Ziploc bag, XRF film, double-sided tape, an acrylic box, a microscope slide, a ceramic-coated frying pan, a stainless-steel sonicator lid, and a stainless-steel rice cooker pot. These materials show very low and mostly flat signals in the fluorine region, as expected. The right graph shows results from positive controls, or materials known to contain fluorine. These include a 1-mil PFA film, PTFE film, PTFE tape, a Teflon-coated pan, a 1-mil PVDF film, a 5.0-micron PVDF filter, a large fluorine rock, and a small fluorine rock. These materials show strong, clear peaks in the fluorine region, especially the films and Teflon pan, indicating a high fluorine content.

Figure 9. XRF spectrum from different levels of fluorine concentrations using the two handheld XRF machines.

This figure shows two graphs comparing how two handheld XRF machines (KC machine on the left and UW machine on the right) detected fluorine in filter paper spiked with known concentrations of fluorine. The horizontal axis shows energy levels, and the vertical axis shows signal strength on a logarithmic scale. Each line represents a different fluorine concentration, with colors ranging from light blue (low concentration) to dark blue (high concentration). In both machines, signal intensity increases with higher fluorine levels, with a clear peak around 0.66 keV. These results demonstrate that both machines reliably detect and respond to increasing fluorine concentrations in the samples.

Figure 10. XRF detector response at different levels of fluorine concentration for each of the two handheld XRFs (King County machine left and UW machine right).

This figure shows two graphs representing how two handheld XRF machines respond to different levels of fluorine in test samples. The graph on the left is for the KC machine, and the one on the right is for UW machine. Each blue dot represents a filter paper sample that was prepared with a known amount of fluorine (measured in parts per million, or ppm) and tested using the XRF machine. The vertical axis shows the fluorine concentration in the sample. The horizontal axis shows the strength of the fluorine signal picked up by the machine, calculated by dividing the fluorine signal (between 0.64 and 0.68 keV) by the total signal from the sample. A curved line is drawn through the dots to show the relationship between fluorine levels and machine response, using a logarithmic equation.

Figure 11. Different testing for PFAS by sample type.

This graphic shows how products (illustrated by a baby bib) were divided into two types of samples for fluorine testing: an intact surface (solid-colored circle) and a homogenized sample (patterned circle created by grinding the material). For XRF testing, the homogenized sample was attached to double-sided tape and mounted on a microscope slide. Arrows indicate that both intact and homogenized samples were tested using handheld XRF and PIGE methods, while only homogenized samples were sent to a laboratory for CIC and LC-MS/MS chemical analysis.

Figure 12. Proportion of fluorine detection by different methods and by product category (only "homogenized" samples shown).

This bar chart shows how many product samples were tested for fluorine and how many had higher or lower levels of it, across five product categories: children's products, cosmetics and personal care, household products, clothing and apparel, and packaging. For each category, three testing methods are shown: CIC, PIGE, and XRF. Each bar is divided into two parts: the teal section shows the number of samples with low fluorine levels (20 parts per million or less), while the red section shows higher fluorine levels (over 20 parts per million). Children's products had the most samples tested, and most showed low fluorine levels across all methods. In contrast, household products had a higher number of samples with elevated fluorine, especially when tested with PIGE. Packaging mostly showed lower fluorine levels.

Figure 13. Correlation matrix (Spearman's correlation) between XRF, PIGE, and CIC fluorine detection results using averaged results from replicate measurements for all products (left) and for products with similar matrices (right). (only "homogenized" samples shown).

These two square charts show how similarly three methods—XRF, PIGE, and CIC—ranked the amount of fluorine found in products. The numbers in each square represent Spearman correlation coefficients, which range from -1 to 1. A number close to 1 means the two methods gave similar rankings (e.g., both found high fluorine in the same samples), a number close to 0 means no clear pattern, and a number close to -1 means opposite rankings. Left chart shows correlations using the average results from all tested products. Right chart shows the same correlations but only for products with similar material types (to reduce variation from different product surfaces). In both charts, the strongest agreement was between CIC and PIGE (0.73 on the left and 0.67 on the right), while XRF showed more moderate correlations with both methods. All numbers are colored according to strength (darker red = stronger correlation), and stars indicate significance levels: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

Figure 14. Fluorine concentration distributions measured by different methods and by product category (only "homogenized" samples shown).

This boxplot shows how much fluorine was found in different product categories using three testing methods: CIC (red), PIGE (green), and XRF (blue). The product categories include children's products, cosmetics and personal care, household products, clothing and apparel, and packaging and containers. The vertical axis shows fluorine concentration in parts per million (ppm), using a special scale (asinh) that helps visualize both very small and very large values, including negative results. Each box shows the typical range of fluorine concentrations for that method and product type, with the line in the middle representing the median value. The lines extending from the box (called whiskers) show the spread of most of the other values, and the black dots represent unusually high or low results (called outliers). CIC and PIGE provided consistent and reliable fluorine measurements across product categories, while XRF showed greater variability and occasional non-physical (negative) values, especially at low concentrations.

Figure 15. Comparison of fluorine measurements using prepared "homogenized" samples versus intact samples using handheld XRF (left) and PIGE (right).

This figure includes two scatterplots comparing fluorine levels measured from intact product surfaces (horizontal axis) and homogenized samples (vertical axis), using two different methods: XRF (left) and PIGE (right). Each dot represents one sample, and the closer the dots are to the line, the more closely the two sample types agree in their results. In the XRF plot, more sample pairs were tested than in the PIGE plot, but the results show greater variation, including some negative values (which are not physically possible). The correlation between intact and homogenized samples using XRF is moderate (rho = 0.53). In contrast, the PIGE results are more consistent, with fewer sample pairs but a much stronger correlation (rho = 0.95).

Figure 16. PFAS detection frequency by PFAS measured in 98 "homogenized" and 2 wipes samples (total of 100 samples from 92 products).

This chart shows how often different PFAS analytes were found in tested samples. Each row lists one PFAS compound, and the number next to it shows how many samples it was detected in. The darker red colors represent chemicals that were found more frequently, while lighter colors or white mean the chemical was found less often, or not at all. The most frequently detected PFAS were PFBS and PFOA, each found in 23 products. Other commonly detected PFAS included PFHxA, PFPeA, and PFDA. Many other PFAS were found in only a few products, and several (at the bottom of the chart) were not detected in any samples tested.

Figure 17. PFAS detection frequency by product category (98 "homogenized" and 2 wipes samples, for a total of 100 samples from 92 products).

This chart shows how often different PFAS analytes were found in five categories of consumer products: children's products, cosmetics and personal care products, household products, clothing and apparel, and packaging and containers. Each row lists a specific PFAS chemical, and each cell shows how many times it was detected in that product category. Darker red colors mean the chemical was detected more frequently; white means it was not found at all. Some PFAS were detected mostly in children's products (like PFBS, found 17 times), while others were more common in household products (such as PFOA, found 13 times). Many PFAS were not detected in cosmetics or packaging categories, and several PFAS were not detected in any product.

Figure 18. PFAS detection by product category (98 "homogenized" and 2 wipes samples, for a total of 100 samples from 92 products).

This bar chart shows how many products in each category were tested for PFAS and whether any of the 40 PFAS analytes were detected. Product categories include children's products, cosmetics and personal care products, household products, clothing and apparel, and packaging and containers. Each bar is divided into two colors: Red means PFAS was found in at least one chemical tested; teal means no PFAS was detected. Children's products and household products had the highest number of samples tested and also the most detections. In contrast, most cosmetics and packaging samples had no detectable PFAS.

Learn More

Diana Ceballos, PhD, MS, CIH
Assistant Professor
University of Washington
Email: dmco25@uw.edu

Partners

Hazardous Waste Management Program

Public Health
Seattle & King County

PURDUE UNIVERSITY