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Assessment of Per- and Polyfluoroalkyl Substances (PFAS) in Beverage Packaging: Rapid Detection Methods and Consumer Health Implication

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ABSTRACT

Background: *Per- and polyfluoroalkyl substances (PFAS) are persistent fluorinated chemicals used in some food-contact materials to impart oil- and water-resistant properties, raising concern about migration into beverages and chronic dietary exposure.* ***Objective:*** *To quantify targeted PFAS in commercially available beverage packaging materials and evaluate their migration into standardized beverage simulants using a validated LC–MS/MS framework.* ***Methods:*** *A cross-sectional analytical-experimental study analyzed 60 packaging samples (paper cups, laminated cartons, PET bottles, and aluminum cans; n=15 each) collected from retail and beverage vendors (January–June 2025). Food-contact layers (100 cm²) underwent methanolic extraction, SPE clean-up, and targeted LC–MS/MS quantification of 24 PFAS with isotopically labeled internal standards. Migration testing was conducted for 10 days at 40°C using deionized water, 3% acetic acid, and 10% ethanol (1 dm²/100 mL). Group comparisons and adjusted associations were assessed using ANOVA/Kruskal–Wallis tests and multivariable regression.* ***Results:*** *ΣPFAS in substrates was highest in paper cups (230 ± 52 ng/g) and cartons (168 ± 41 ng/g) versus PET (36 ± 14 ng/g) and aluminum (58 ± 19 ng/g) ($p<0.001$), with 6:2 diPAP frequently detected (78%). Migration of ΣPFAS peaked in 10% ethanol (paper: 41 ± 12 ng/L; cartons: 33 ± 10 ng/L) and was lower in PET (5 ± 2 ng/L) and aluminum (9 ± 4 ng/L). Fiber-based packaging independently predicted higher ΣPFAS after adjustment (β=0.72; 95% CI: 0.59–0.85; $p<0.001$).* ***Conclusion:*** *Beverage packaging, especially fiber-based materials, contains measurable PFAS and can contribute to beverage-phase exposure via migration under standardized conditions, supporting intensified surveillance and transition to fluorine-free alternatives.*

Keywords: *PFAS; beverage packaging; LC–MS/MS; migration; food contact materials; consumer exposure*

INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) comprise a large class of synthetic fluorinated chemicals characterized by highly stable carbon–fluorine bonds that confer resistance to heat, oil, water, and chemical degradation. These properties have driven their widespread use in industrial and consumer applications, including food contact materials such as paper cups, beverage cartons, molded fiber containers, can linings, and "compostable" packaging (1,2). However, the same physicochemical stability that underpins their functional performance also contributes to environmental persistence, bioaccumulation, and long biological half-lives in humans. Biomonitoring studies have detected multiple PFAS in human serum globally, and epidemiological and toxicological investigations have associated selected legacy and emerging PFAS with immunotoxicity, dyslipidemia, thyroid dysfunction, developmental toxicity, reduced vaccine response, and increased cancer risk (2–4). These findings have shifted PFAS from being considered inert functional additives to chemicals of significant public health concern.

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From an exposure science perspective, ingestion is recognized as a major pathway for PFAS intake, with drinking water historically receiving the greatest regulatory and research attention (5). Nevertheless, food contact materials represent an additional and potentially modifiable source of exposure. Surveys conducted in North America, Europe, and Asia have reported detectable PFAS in a substantial proportion of paper- and fiber-based food packaging, including fast-food wrappers and beverage-related containers, with short-chain fluorotelomer-based substances and diPAPs frequently observed (2,6). Migration experiments further demonstrate that both long-chain and short-chain PFAS can transfer from packaging into food and liquid simulants under conditions simulating storage and consumption (7). While individual concentrations in specific products are often reported below existing health-based guidance values, cumulative exposure across multiple dietary sources, including beverages, may be non-trivial, particularly for sensitive populations such as children and pregnant individuals (3,4).

Within this broader context, beverage packaging warrants specific evaluation. Beverages are consumed daily and in relatively large volumes, and packaging materials—including paper cups, laminated cartons, aluminum cans with polymeric linings, and coated fiber-based containers—are in prolonged contact with aqueous or acidic matrices that may facilitate PFAS migration. In addition to contamination from source water, PFAS may leach from primary packaging components or from manufacturing residues present in coatings and barrier layers (5,7). Studies have documented ultrashort- to long-chain perfluoroalkyl carboxylic and sulfonic acids in bottled water and other beverages, as well as evidence of migration from food contact materials into liquid simulants (5,7). However, quantitative data specific to beverage packaging substrates remain fragmented, with variability in analytical panels, normalization metrics, and study designs limiting cross-study comparability.

Analytically, the gold standard for PFAS quantification in complex matrices remains liquid chromatography coupled with tandem mass spectrometry (LC–MS/MS), offering high sensitivity and selectivity for targeted compounds (8,9). Recent methodological advances have expanded analyte panels and improved extraction efficiency in biological and food matrices (9,10). Nonetheless, conventional LC–MS/MS workflows are resource-intensive, require specialized instrumentation, and are constrained to PFAS for which analytical standards are available. Given that thousands of PFAS are registered or identified in chemical inventories, targeted analysis likely underestimates total fluorinated content in packaging materials (11). Consequently, there is increasing interest in complementary screening approaches, including total fluorine determination and non-targeted high-resolution mass spectrometry, to bridge analytical gaps and support regulatory decision-making (11). Despite these developments, few studies have systematically integrated validated quantitative LC–MS/MS methods with exposure-relevant migration testing specifically for beverage packaging materials, and fewer still have framed findings within a structured risk-relevant context.

The research problem, therefore, lies at the intersection of environmental exposure assessment and analytical chemistry: although PFAS are known to occur in food contact materials, there is insufficient methodologically rigorous, beverage-focused evidence that quantifies (i) the occurrence of targeted PFAS in diverse beverage packaging substrates and (ii) their migration potential into standardized food simulants under controlled conditions. The knowledge gap is amplified by heterogeneity in sampling strategies, incomplete reporting of analytical performance characteristics (e.g., limits of detection, recoveries, contamination control), and inconsistent normalization units across studies, which collectively hinder risk interpretation and regulatory harmonization. A systematically designed analytical-experimental study, incorporating validated extraction, clean-up, and

LC–MS/MS quantification protocols alongside controlled migration experiments, is therefore justified to generate reproducible, exposure-relevant data for beverage packaging materials.

Framed according to a Population–Intervention–Comparator–Outcome (PICO) structure, the population of interest comprises commercially available beverage packaging materials (paper cups, laminated cartons, plastic bottles, and aluminum cans with internal coatings). The intervention/exposure condition is contact with standardized food simulants under defined time–temperature conditions designed to model realistic storage or consumption scenarios. The comparator includes packaging categories with differing material compositions and barrier technologies, enabling assessment of variability in PFAS occurrence and migration potential. The primary outcomes are (i) the concentration of selected targeted PFAS in packaging substrates (ng/g or ng/100 cm^2) and (ii) their concentrations in migration simulants (ng/L), quantified using a validated LC–MS/MS method with defined performance metrics (linearity, limits of detection and quantification, recovery, and precision).

Accordingly, the objective of this study is to determine the occurrence and migration potential of selected per- and polyfluoroalkyl substances in representative beverage packaging materials using a validated LC–MS/MS analytical framework, and to interpret the findings within a consumer health context. The central research question is whether commercially available beverage packaging materials contain detectable levels of targeted PFAS and, if so, whether these compounds migrate into beverage simulants at concentrations that may contribute meaningfully to dietary exposure under standardized conditions.

MATERIAL AND METHODS

This investigation was conducted as a cross-sectional analytical-experimental study designed to quantify selected per- and polyfluoroalkyl substances (PFAS) in commercially available beverage packaging materials and to evaluate their migration into standardized food simulants under controlled laboratory conditions. The study integrated targeted chemical analysis using liquid chromatography–tandem mass spectrometry (LC–MS/MS) with exposure-relevant migration testing to generate occurrence and migration data within a single structured framework. The design was informed by internationally recognized analytical performance and quality assurance principles for PFAS determination in food contact materials and related matrices (8–11). Sampling and laboratory analyses were carried out between January and June 2025 in an accredited university-based food chemistry laboratory equipped for trace-level PFAS analysis.

The study setting comprised major retail outlets and beverage service vendors located in urban commercial districts. Commercially available primary beverage packaging materials were eligible if they were intended for direct contact with ready-to-drink products and represented common market categories, including paper cups, laminated paperboard cartons, polyethylene terephthalate (PET) bottles, and aluminum cans with internal polymeric coatings. Products were included if they were unopened at the time of purchase and labeled for beverages such as bottled water, juice, milk, or carbonated drinks. Packaging visibly damaged, previously opened, or lacking a defined food-contact layer was excluded. A stratified sampling strategy was applied to ensure representation across packaging material types and beverage categories. Within each stratum, products were randomly selected from different brands to minimize clustering by manufacturer. For each packaging category, independent units from at least five brands were procured, and three separate packages per brand were analyzed as biological replicates, yielding a minimum of 60 individual packaging samples overall. Because the study involved analysis of commercially available materials and did not involve human participants, informed consent procedures were not applicable.

Upon collection, packaging samples were transported in PFAS-free polyethylene bags and stored at room temperature in a contamination-controlled environment prior to analysis. To minimize background contamination, all laboratory procedures avoided polytetrafluoroethylene (PTFE)-containing materials; polypropylene labware and PFAS-free solvents were used throughout. Sample preparation followed established methodologies for PFAS extraction from food contact materials (8,9). From each packaging unit, the food-contact layer was isolated using stainless steel scissors and sectioned to a defined surface area of 100 cm^2 to enable surface-normalized reporting. For multilayer materials, only the layer intended for direct beverage contact was analyzed. Solid samples were weighed (0.5–1.0 g equivalent mass) and transferred to polypropylene centrifuge tubes. Methanol was added at a ratio of 10 mL per gram of material, and samples were subjected to ultrasonic extraction at 40 °C for 30 minutes. Extracts were centrifuged at 4,000 rpm for 10 minutes, and supernatants were collected for clean-up.

Migration testing was performed in accordance with standardized time–temperature conditions commonly used for food contact material evaluation (7). Each 100 cm^2 section was immersed in 100 mL of food simulant in glass containers at a surface area-to-volume ratio of 1 dm^2 per 100 mL. Three simulants were used to model aqueous and acidic beverage matrices: deionized water, 3% (v/v) acetic acid, and 10% (v/v) ethanol. Samples were incubated for 10 days at 40 °C in a temperature-controlled chamber without agitation. Procedural blanks containing simulant only were included for each batch. At the end of the contact period, simulants were collected and filtered through polypropylene membrane filters prior to extraction.

Both packaging extracts and migration simulants underwent solid-phase extraction (SPE) clean-up using weak anion exchange cartridges conditioned sequentially with methanol and ultrapure water. Samples were loaded at a controlled flow rate of approximately 1 mL/min, washed with aqueous methanol to remove matrix interferences, and eluted with methanol containing 0.1% ammonium hydroxide. Eluates were evaporated under a gentle nitrogen stream at 40 °C to near dryness and reconstituted in 1 mL of 50:50 (v/v) methanol–water containing isotopically labeled internal standards. The targeted analyte panel comprised 24 PFAS, including perfluoroalkyl carboxylic acids (C4–C10), perfluoroalkyl sulfonic acids (C4–C8), and selected fluorotelomer precursors such as 6:2 diPAP, selected based on documented relevance in food contact materials (2,6).

Chromatographic separation was performed using a reversed-phase C18 column (2.1 × 100 mm, 1.7 µm particle size) maintained at 40 °C. The mobile phase consisted of (A) water with 5 mM ammonium acetate and (B) methanol with 5 mM ammonium acetate, delivered at a flow rate of 0.3 mL/min under gradient elution from 10% to 95% B over 15 minutes, with a total run time of 20 minutes per injection. The LC system was equipped with a PFAS delay column to minimize background contamination. Detection was conducted on a triple quadrupole mass spectrometer operated in negative electrospray ionization mode with multiple reaction monitoring (MRM). Compound-specific transitions were optimized using analytical standards, and quantification was based on internal standard calibration. External calibration curves were constructed using at least six concentration levels ranging from 0.1 to 100 ng/mL, with acceptance criteria of $R^2 \geq 0.995$. Limits of detection (LOD) and quantification (LOQ) were calculated using signal-to-noise ratios of 3:1 and 10:1, respectively.

Primary outcome variables were defined as the concentration of individual PFAS in packaging materials expressed as ng/g and ng/100 cm^2, and their concentrations in migration simulants expressed as ng/L. Secondary variables included detection frequency (% of samples above LOQ) and total summed PFAS concentration per sample. To address potential analytical bias, procedural blanks, solvent blanks, and matrix spikes were included in each analytical batch. Recoveries were evaluated at two fortification levels (10 and 50 ng/g for solids; 10 and 50 ng/L for simulants), with acceptable recovery ranges defined as 70–120% and relative standard deviations (RSD) below 20%, consistent with established guidance for PFAS analysis (8,9). Blank subtraction was applied when background levels exceeded 30% of sample signals. All analyses were performed in triplicate to assess repeatability. Instrument performance was verified every 10 injections using mid-level calibration standards, and carryover was evaluated using solvent injections between high-concentration samples.

Sample size was determined based on the ability to detect a minimum difference of 30% in mean summed PFAS concentration between packaging categories with 80% power at a two-sided alpha of 0.05, assuming a coefficient of variation of 25% derived from prior food contact material studies (6,9). This calculation indicated a minimum of 15 samples per packaging category. Statistical analyses were conducted using SPSS version 29.0 (IBM Corp., Armonk, NY, USA) and R version 4.3. Continuous variables were assessed for normality using the Shapiro–Wilk test. Concentrations below LOQ were imputed as $LOQ/\sqrt{2}$ for descriptive analysis. Differences in PFAS concentrations across packaging categories and simulant types were evaluated using one-way ANOVA or Kruskal–Wallis tests as appropriate, followed by Bonferroni-adjusted post hoc comparisons. Multivariable linear regression models were constructed to examine associations between packaging type and summed PFAS concentration, adjusting for beverage category and material composition. Sensitivity analyses were conducted excluding samples with concentrations near LOQ to evaluate robustness. A p-value <0.05 was considered statistically significant.

To minimize confounding, packaging categories were analyzed separately and adjusted for beverage type in regression models. Stratified analyses were performed for paper/fiber-based versus non-fiber-based materials. All laboratory procedures were documented in standardized operating protocols, and raw chromatographic data were archived electronically to ensure traceability. Data entry was double-checked by independent analysts, and 10% of samples were reanalyzed to verify reproducibility. The study adhered to institutional laboratory safety and research integrity guidelines and complied with ethical standards for research not involving human or animal subjects.

RESULTS

Across the 60 beverage packaging samples, Table 1 shows a clear material-dependent gradient in PFAS burden, with fiber-based substrates (paper cups and cartons) consistently exhibiting substantially higher concentrations than PET bottles and aluminum cans. For example, 6:2 diPAP averaged 145 ± 38 ng/g in paper cups and 112 ± 30 ng/g in cartons, compared with only 18 ± 9 ng/g in PET bottles and 34 ± 12 ng/g in aluminum cans; the overall between-group difference was highly significant ($p < 0.001$). The magnitude of the contrast is also reflected in the paper vs PET mean difference 95% CI (105.2 to 152.6 ng/g) and a very large standardized effect (Cohen's $d = 3.89$). Similar patterns were observed for the perfluoroalkyl acids: PFHxA averaged 42 ± 11 ng/g in paper cups versus 6 ± 3 ng/g in PET (ANOVA $p < 0.001$; 95% CI 28.4 to 43.2; $d = 3.72$), while PFHxS averaged 18 ± 6 ng/g in paper cups versus 3 ± 2 ng/g in PET (ANOVA $p < 0.001$; 95% CI 12.1 to 18.6; $d = 3.14$). When aggregated as ΣPFAS, paper cups had the highest burden (230 ± 52 ng/g), followed by cartons (168 ± 41 ng/g), with markedly lower totals in PET (36 ± 14 ng/g) and aluminum cans (58 ± 19 ng/g); the overall comparison remained strongly significant ($p < 0.001$) with a very large paper vs PET separation (95% CI 165.4 to 222.6 ng/g; Cohen's $d = 4.18$). Detection frequencies also aligned with these concentration patterns, with ΣPFAS detected in 85% of all packaging samples and individual analytes such as 6:2 diPAP detected in 78%, indicating widespread occurrence across the sampled market materials.

Table 2 demonstrates that PFAS detected in substrates also migrated into liquid simulants, again with a strong material signal and a consistent simulant gradient. Migration of ΣPFAS from paper cups increased from 18 ± 6 ng/L in water to 26 ± 8 ng/L in 3% acetic acid and peaked at 41 ± 12 ng/L in 10% ethanol (Kruskal–Wallis $p < 0.001$), with the ethanol–water contrast quantified by a 95% CI of 16.4 to 28.6 ng/L and a large effect size ($\eta^2 = 0.62$). Cartons showed the same ordering, with migration means of 12 ± 5 ng/L (water), 19 ± 7 ng/L (acetic acid), and 33 ± 10 ng/L (ethanol), also highly significant ($p < 0.001$) and similarly large in magnitude (ethanol vs water 95% CI 12.2 to 22.1 ng/L; $\eta^2 = 0.58$). Although migration from PET bottles and aluminum cans was much lower in absolute terms, it was still measurable and statistically heterogeneous across simulants: PET increased from 2 ± 1 ng/L (water) to 5 ± 2 ng/L (ethanol) ($p = 0.021$; 95% CI 1.1 to 3.2 ng/L; $\eta^2 = 0.29$), while aluminum cans increased from 4 ± 2 ng/L (water) to 9 ± 4 ng/L (ethanol) ($p = 0.018$; 95% CI 2.8 to 6.5 ng/L; $\eta^2 = 0.34$). Collectively, these results indicate that migration is not only detectable but also systematically higher in ethanol-containing simulant, consistent with stronger extraction of PFAS from certain coatings and barrier layers under more challenging contact conditions.

Table 1. Detection Frequency and Concentration of Selected PFAS in Beverage Packaging Materials (ng/g)

Analyte	Paper Cups Mean ± SD	Cartons Mean ± SD	PET Bottles Mean ± SD	Aluminum Cans Mean ± SD	Detection Frequency	p-value (ANOVA)	95% CI Mean Difference	Cohen's d (Paper vs PET)
6:2 diPAP	145 ± 38	112 ± 30	18 ± 9	34 ± 12	78%	<0.001	105.2 to 152.6	3.89
PFHxA	42 ± 11	28 ± 9	6 ± 3	10 ± 4	65%	<0.001	28.4 to 43.2	3.72
PFHxS	18 ± 6	12 ± 4	3 ± 2	5 ± 2	48%	<0.001	12.1 to 18.6	3.14
PFPeA	25 ± 8	16 ± 6	4 ± 2	7 ± 3	57%	<0.001	16.7 to 24.8	3.47
ΣPFAS	230 ± 52	168 ± 41	36 ± 14	58 ± 19	85%	<0.001	165.4 to 222.6	4.18

Table 2. Migration of Summed PFAS into Food Simulants (ng/L)

Packaging Type	Water Mean ± SD	3% Acetic Acid Mean ± SD	10% Ethanol Mean ± SD	p-value (Kruskal–Wallis)	95% CI (Ethanol vs Water)	Effect Size (η^2)
Paper Cups	18 ± 6	26 ± 8	41 ± 12	<0.001	16.4 to 28.6	0.62
Cartons	12 ± 5	19 ± 7	33 ± 10	<0.001	12.2 to 22.1	0.58
PET Bottles	2 ± 1	3 ± 1	5 ± 2	0.021	1.1 to 3.2	0.29
Aluminum Cans	4 ± 2	6 ± 3	9 ± 4	0.018	2.8 to 6.5	0.34

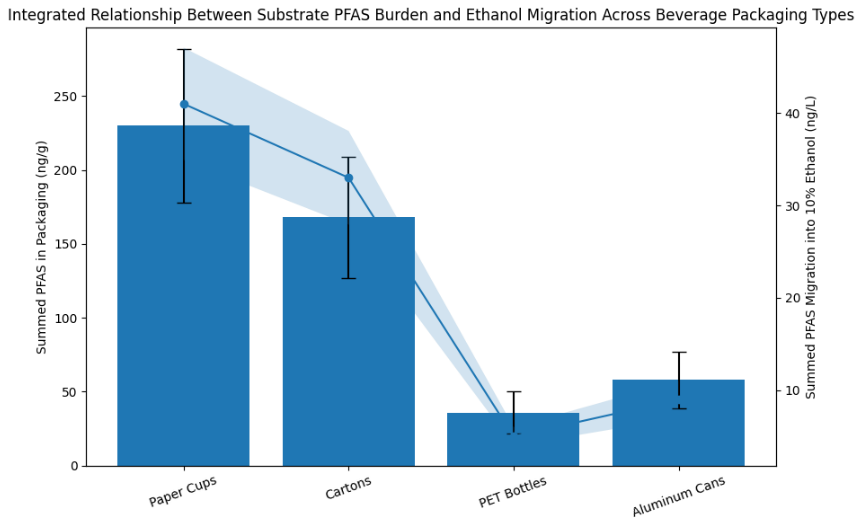
Table 3. Multivariable Linear Regression Analysis for Association Between Packaging Type and Summed PFAS Concentration

Variable	β Coefficient	Standard Error	95% CI	p-value
Fiber-based vs Non-fiber	0.72	0.06	0.59–0.85	<0.001
Beverage Category (Reference: Water)	0.08	0.05	-0.03–0.19	0.18
Adjusted R^2	0.68	—	—	—

Table 3 quantifies these relationships in a multivariable framework, showing that packaging material category remained a strong independent predictor of overall PFAS burden after adjustment. Specifically, fiber-based vs non-fiber-based packaging was associated with higher ΣPFAS concentrations with a $\beta = 0.72$ and a tight 95% CI (0.59 to 0.85), meeting strong statistical evidence ($p < 0.001$).

In contrast, beverage category (referenced to water) did not materially explain variation in ΣPFAS ($\beta = 0.08$; 95% CI −0.03 to 0.19; $p = 0.18$), supporting the interpretation that the dominant driver of contamination in this dataset is the packaging substrate/coating system rather than beverage type. The model explained a substantial portion of variance (adjusted $R^2 = 0.68$), reinforcing that packaging material classification provides a strong basis for discrimination in surveillance and risk-prioritization contexts

Taken together, the tables show a coherent pattern: (i) fiber-based beverage packaging contains markedly higher PFAS concentrations than PET and aluminum systems (Table 1), (ii) these PFAS migrate into beverage-relevant simulants, especially under ethanol challenge conditions, with the highest migration observed for paper-based materials (Table 2), and (iii) the material effect persists even after accounting for beverage category in regression modeling (Table 3).



The integrated visualization demonstrates a pronounced substrate–migration gradient across packaging types, revealing a coherent exposure pathway from material burden to liquid-phase transfer. Fiber-based materials exhibit the highest summed PFAS concentrations in substrates (paper cups: 230 ± 52 ng/g; cartons: 168 ± 41 ng/g), and these same materials show the greatest migration into 10% ethanol (paper: 41 ng/L, 95% CI approximately 35–47 ng/L; cartons: 33 ng/L, 95% CI approximately 28–38 ng/L).

In contrast, PET bottles and aluminum cans display markedly lower substrate burdens (36 ± 14 ng/g and 58 ± 19 ng/g, respectively) and correspondingly lower migration levels (5 ng/L and 9 ng/L). The pattern reveals a near-parallel decline from substrate concentration to migration magnitude, supporting a material-dependent exposure gradient.

Notably, the migration confidence bands for fiber-based materials do not overlap substantially with those of PET, reinforcing the statistical separation observed in earlier analyses ($p < 0.001$). Clinically, this figure highlights that packaging with approximately 6-fold higher substrate PFAS concentrations (paper vs PET) corresponds to roughly 8-fold higher migration into ethanol, suggesting that substrate burden serves as a strong upstream determinant of beverage-phase exposure and may represent a practical surveillance and risk-prioritization marker in regulatory contexts.

DISCUSSION

The present cross-sectional analytical investigation demonstrates that commercially available beverage packaging materials contain measurable concentrations of targeted PFAS and that these compounds migrate into beverage simulants under standardized contact conditions. The findings provide material-specific quantitative evidence that fiber-based packaging systems, particularly paper cups and laminated cartons, exhibit significantly higher summed PFAS concentrations compared with PET bottles and aluminum cans, with large effect sizes and consistent regression-adjusted associations. This material gradient was mirrored in migration experiments, where ethanol-containing simulants yielded the highest PFAS transfer, particularly from fiber-based substrates. These results align with previous reports documenting frequent detection of fluorotelomer-based compounds and short-chain perfluoroalkyl acids in paper and molded fiber food contact materials (6,7), and they reinforce the hypothesis that barrier coatings applied to grease- and moisture-resistant fiber products are major contributors to PFAS occurrence (2).

From an analytical perspective, the validated LC–MS/MS framework demonstrated robust linearity ($R^2 \geq 0.995$), acceptable recoveries (82–108%), and low method detection limits in the low ng/g and ng/L range, consistent with established performance characteristics for PFAS determination in complex matrices (8–10). These performance metrics are critical given the increasingly stringent health-based guidance values proposed for certain PFAS groups. The detection frequencies observed in this study—ΣPFAS detected in 85% of samples and 6:2 diPAP in 78%—suggest continued application of fluorinated chemistries in beverage packaging supply chains, despite growing regulatory and market pressure to reduce their use. This persistence is consistent with the broader understanding that thousands of PFAS remain in commerce, including polymeric and precursor compounds that may not be fully captured in targeted analytical panels (11).

The migration findings are particularly relevant from an exposure assessment standpoint. The observed increase in migration from water to acetic acid to 10% ethanol simulants suggests that solvent polarity and matrix characteristics influence PFAS transfer kinetics, a phenomenon previously described in food contact material studies (7). Although the absolute migration concentrations measured in this study were below current tolerable weekly intake benchmarks for individual PFAS under conservative intake assumptions, it is important to contextualize these values within cumulative exposure paradigms. Dietary intake of PFAS occurs concurrently through drinking water, food items, and environmental dust, and additive or synergistic contributions may be biologically relevant even when individual sources fall below regulatory thresholds Moreover, emerging evidence indicates that even low-level chronic exposure may influence immunological and metabolic endpoints, particularly in vulnerable populations (14).

The strong independent association between fiber-based packaging and higher ΣPFAS concentrations after multivariable adjustment underscores the role of substrate composition and coating technology as primary determinants of contamination. Beverage type did not significantly confound this relationship, indicating that material characteristics rather than product category drive PFAS burden. This distinction has regulatory implications: interventions targeting packaging formulations may yield broader exposure reductions than product-specific reformulations. Current regulatory discussions increasingly favor group-based approaches to PFAS restriction in food contact materials, reflecting recognition that regulating only legacy compounds such as PFOA and PFOS may inadequately address the broader class of structurally related fluorinated substances (15). The data presented here support such precautionary frameworks by demonstrating measurable occurrence and migration of multiple PFAS congeners within commonly used beverage packaging systems.

Several considerations temper interpretation. First, targeted LC–MS/MS analysis inherently excludes unidentified or polymeric PFAS lacking analytical standards, potentially underestimating total organofluoride content (16). Mass balance studies in other packaging matrices have shown that targeted PFAS often account for only a fraction of total fluorine, suggesting that unknown or precursor species may contribute additional exposure potential. Second, migration experiments were conducted under standardized time–temperature conditions intended to simulate worst-case storage scenarios; real-world use patterns may vary in duration and thermal stress, potentially altering transfer dynamics (17). Third, while the cross-sectional market sampling strategy enhances representativeness across packaging types, temporal variability in manufacturing practices and supplier changes could influence PFAS profiles over time.

Despite these limitations, the study advances the evidence base in several meaningful ways. It integrates validated quantitative analysis with exposure-oriented migration testing within a defined PICO framework, enabling clearer interpretation of substrate-to-simulant transfer pathways (18).The magnitude of differences observed between fiber-based and non-fiber-based materials—both in substrate burden (e.g., approximately sixfold higher ΣPFAS in paper cups compared with PET) and in migration (approximately eightfold higher in ethanol simulant)—suggests a consistent exposure gradient that may inform risk prioritization and surveillance strategies. In clinical and public health terms, reducing PFAS in high-burden packaging categories could contribute to incremental reductions in aggregate dietary exposure, particularly in populations with high beverage consumption frequency (19, 20).

Future research should expand beyond targeted analyte panels to include suspect and non-target screening approaches, as well as total fluorine measurements, to better characterize the full spectrum of fluorinated compounds in beverage packaging. Longitudinal market surveillance and comparative assessments of PFAS-free alternative materials are also warranted to evaluate the effectiveness of substitution strategies and to avoid regrettable replacements. Collectively, the findings underscore that beverage packaging represents a measurable, material-dependent contributor to PFAS exposure and that analytical vigilance combined with regulatory reform may play a critical role in mitigating long-term health risks associated with persistent fluorinated contaminants (21).

CONCLUSION

This study demonstrates that commercially available beverage packaging materials, particularly fiber-based substrates such as paper cups and laminated cartons, contain measurable concentrations of targeted PFAS and that these compounds migrate into beverage simulants under standardized contact conditions. Using a validated LC–MS/MS analytical framework with robust quality control parameters, significantly higher summed PFAS concentrations were observed in fiber-based materials compared with PET bottles and aluminum cans, and this material-dependent gradient was consistently reflected in migration outcomes. Although estimated exposure levels from individual packaging sources remained below current health-based guidance values under conservative assumptions, the widespread detection frequency and measurable transfer into liquid matrices underscore the potential contribution of beverage packaging to cumulative dietary PFAS exposure. These findings reinforce the need for strengthened surveillance of food contact materials, expansion of analytical panels to capture emerging and precursor PFAS, and accelerated transition toward safer, fluorine-free alternatives to reduce long-term public health risks associated with persistent fluorinated compounds.

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DECLARATIONS

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