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Article

Hold My Beer: The Linkage between Municipal Water and Brewing Location on PFAS in Popular Beverages

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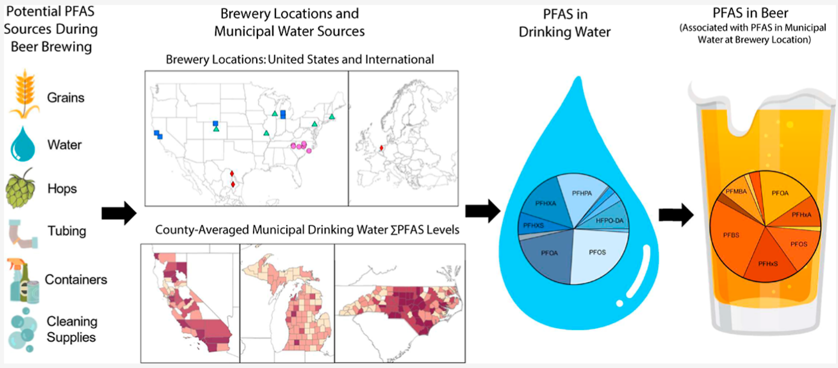

ABSTRACT: Beer has been a popular beverage for millennia. As water is a main component of beer and the brewing process, we surmised that the polyfluoroalkyl substances (PFAS) presence and spatial variability in drinking water systems are a PFAS source in beers. This is the first study to adapt EPA Method 533 to measure PFAS in beer from various regions, brewery types, and water sources. Statistical analyses were conducted to correlate PFAS in state-reported drinking water, and beers were analyzed by brewing location. PFAS were detected in most beers, particularly from smaller scale breweries located near drinking water sources with known PFAS. Perfluorosulfonic acids, particularly PFOS, were frequently detected, with PFOA or PFOS above U.S. EPA's Maximum Contaminant Limits in some beers. There was also a county−level correlation between the total PFAS, PFOA, and PFBS concentrations in drinking water and beers. Given that approximately 18% of U.S. breweries are located within zip codes with detectable PFAS in municipal drinking water, our findings, which link PFAS in beer to the brewery water source, are intended to help inform data-driven policies on PFAS in beverages for governmental agencies, provide insights for brewers and water utilities on treatment needs, and support informed decision-making for consumers.

KEYWORDS: *PFAS, beer, beverages, municipal drinking water, environmental exposure*

1. INTRODUCTION

Beer has been a staple beverage since premodern times, when it was actually considered safer than water given the destruction of waterborne pathogens during brewing.[1,2] Today, beer is the third most popular beverage around the world, following only water and tea.[3] In the United States, the beer industry experienced rapid growth the last several decades, with a market over $400 billion.[4] Smaller craft breweries have experienced massive growth and now comprise a quarter of the U.S. market.[5,6] Macrobreweries produce greater than 15,000 beer barrels or 460,000 U.S. gallons annually.[7]

Beer is comprised primarily of water, malt from grains (usually barley), hops, and yeast.[8] Each individual beer type is characterized by overall style, flavor, aroma, appearance, and feel, with microbreweries often known for a variety of types, from India Pale Ales to Stouts, while larger beer companies predominantly sell lighter beer. Water is the most abundant (>90%) and important ingredient, impacting its pH, enzyme activity, hop utilization, and yeast growth.[9,10] In fact, as much as 7 L of water can be used to produce 1 L of beer, potentially introducing contaminants during beer production.[11] Breweries typically have basic water filtration and treatment processes to ensure source water meets brewing requirements.[12] While these processes aim to balance water parameters for brewing, they are not necessarily effective at removing per- and polyfluoroalkyl substances (PFAS).[13−16]

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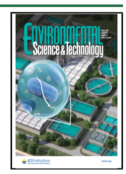

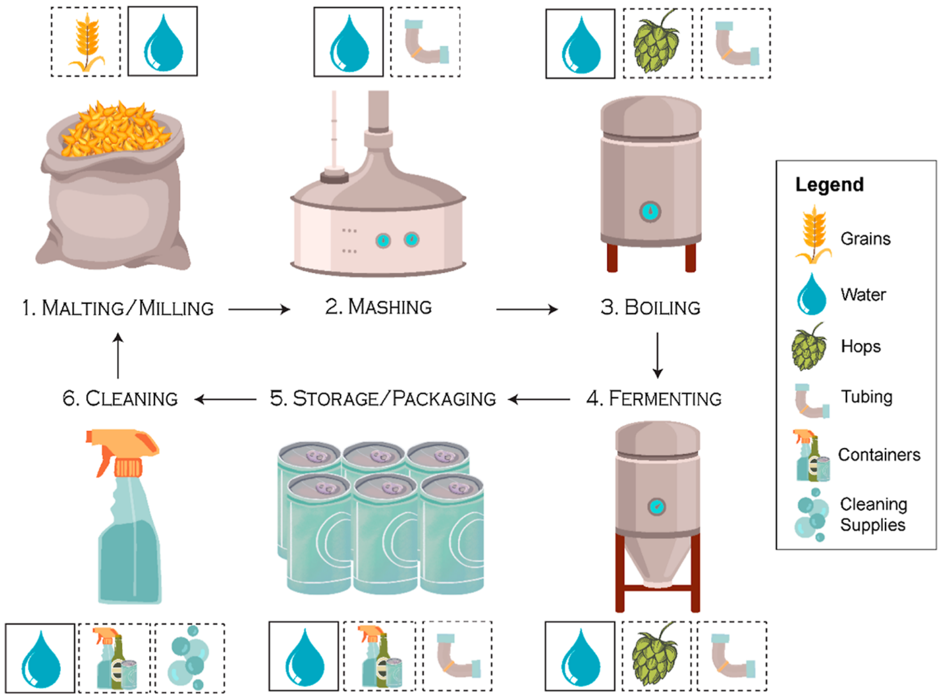

Figure 1. Diagram showing major steps of the beer brewing process along with potential sources of PFAS at each step. Icons within solid lines indicate suspected primary sources of PFAS contamination, while icons within dashed lines indicate possible sources of additional PFAS contamination. Brewing steps vary slightly by beer type and brewer preferences.

PFAS are human-made chemicals produced for their antigrease, water-resistant, and stain-repelling properties.[17] PFAS have been widely used in consumer products (such as carpets, furniture, clothes, cookware, and food packaging), industrial manufacturing (e.g., as a processing aid in plastic production), and in firefighting foam for decades.[17] Often referred to as "forever chemicals", they are ubiquitous in the environment due to their extensive use and resistance to degradation. Recent studies show that PFAS exposure can lead to adverse reproductive, developmental, cardiovascular, liver, kidney, immunological, and carcinogenic health effects.[18−20] Additionally, PFAS can remain in the body for years.[21]

Nearly every American has PFAS in their blood, indicating that exposure is common.[22] Consumption of contaminated drinking water is a major, if not primary contributor to total exposure.[23] PFAS occurrence in the environment has been documented in surface water,[24,25] groundwater,[26] well water,[27,28] and municipal water supplies[18,19,28,29] across the United States and globally,[30,31] with the extent, distribution, and type of PFAS dependent on local factors related to sources. From 2013 to 2015, the U.S. Environmental Protection Agency (USEPA) requested that large public drinking water systems test PFAS to understand the spatial extent and prevalence.[32] The Third Unregulated Contaminant Monitoring Rule (UCMR3) revealed significant concentrations of several PFAS compounds. In 2023, USEPA established maximum contaminant levels (MCLs) for six PFAS in drinking water and the ongoing UCMR program (now UCMR5) will include PFAS results for additional U.S. based municipal water systems.[33]

With the global pervasiveness and variability of PFAS in drinking water sources, paired with the popularity of beer as an adult beverage, we set out to understand whether popular craft beers as well as national and international beers may also be a contributor to total PFAS exposure for beer drinkers. Stable isotope ratios of oxygen and hydrogen show that brewery location strongly correlates with local meteoric water level, indicating that source water in the brewing process is typically local tap water, thus tap water containing PFAS may be an unexpected exposure source for beer consumers.[34] The potential for PFAS contamination in beer can occur at different stages of the brewing process, depending on the source and treatment of water, ingredients, and equipment used. The brewing process involves six main steps: malting, mashing, boiling, fermenting, storage, packaging, and cleaning. Additional PFAS sources could include brewing ingredients (e.g., grains, hops, spices, etc.), packaging or storing materials (storage tanks, tubing, bottles, or cans), and cleaning supplies and processes (Figure 1).

To date, there has been limited information characterizing PFAS in beers and other alcoholic beverages. Only one 2014 study evaluated three types of beers in Germany for 11 PFAS before the establishment of EPA Method 537.1 and 533 (n = 93),[35,36] though the authors postulated PFAS may be in up to 50% of beers worldwide.[10] Another study looked at one fluorinated chemical, trifluoroacetate (TFA), in beer (n = 104) and tea from various countries, albeit also primarily Germany; they found that TFA was common in these beverages and malt was a main source.[37] A consumer advocacy organization has also recently analyzed PFAS in a small number of carbonated (n = 12) and uncarbonated (n = 35) bottled waters available for purchase in the United States.[38]

Given drinking water's critical role in the brewing process, the extent of PFAS in drinking water systems, and limited studies conducted to-date, we aimed to (1) adapt EPA Method 533 to analyze PFAS in beer samples for the first time, (2) investigate whether PFAS were detectable in beers by different company size and geographic location, and (3) understand if PFAS in municipal U.S. water supplies where brewing occurs are a significant contributor to PFAS levels in beer available for

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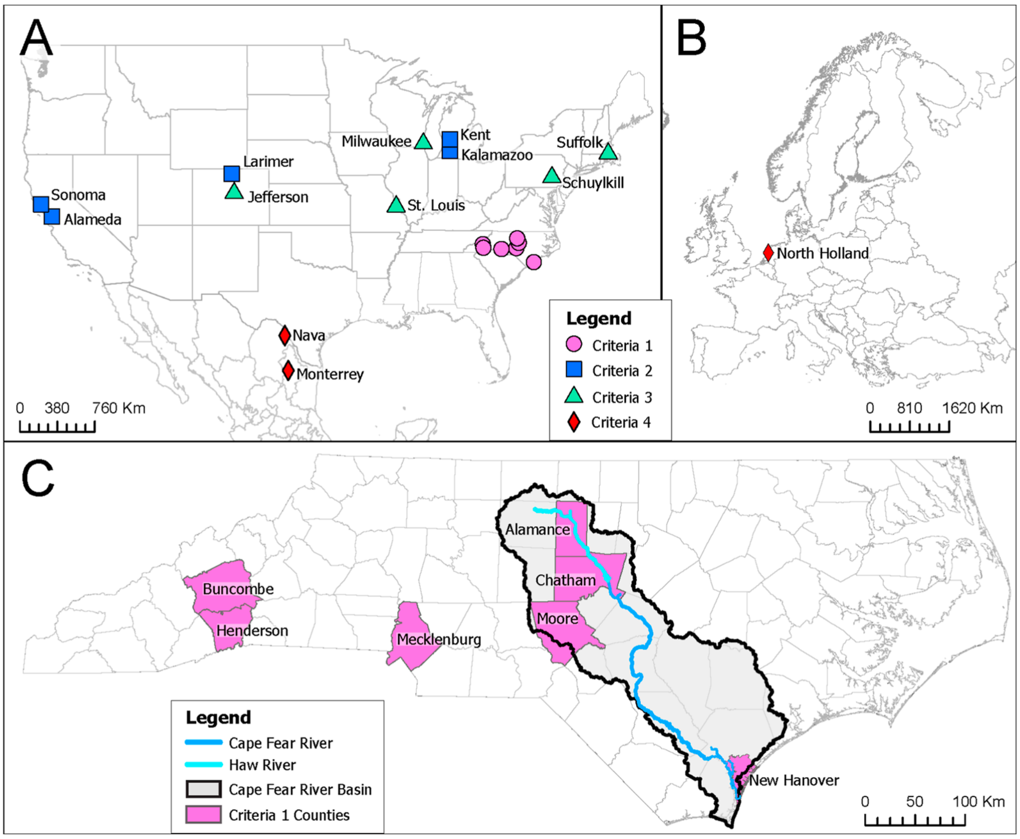

Figure 2. Maps showing brewery locations and criteria in (A) U.S. counties and Mexican municipalities, (B) Europe, and (C) North Carolina counties with brewing locations of purchased beers, the Cape Fear River Basin (gray with a bold black outline), the Haw River (light blue line), and Cape Fear River (blue line). Criteria for beer selection: Pink circles (Criteria 1), blue squares (Criteria 2), teal triangles (Criteria 3), and red diamonds (Criteria 4).

purchase in the United States. Our findings from the first study of PFAS in beer using modified EPA Method 533 and evaluating various companies and brewing locations are intended to help inform data-driven policies on PFAS in beverages for governmental agencies, provide insights for beer brewers who could modify their brewing process to minimize PFAS, and allow consumers make more informed choices.

2. METHODS

2.1. Sample Collection. Regions in the United States with high levels of PFAS in drinking water were identified (UCMR3 and EWG's PFAS Contamination Mapper).[32,39−41] We selected primarily plain lagers and ales from each company/brewery for consistency and because lighter beers were less onerous to prepare, clean, and analyze with laboratory equipment. Our beer selection types (n = 23) considered four criteria/areas overall: Criteria 1—Beers brewed in North Carolina, particularly where high levels of PFAS had been detected in drinking water [e.g., Cape Fear River Basin] (n=10);[14,42,43] Criteria 2- Beers in other U.S. states that were highlighted by UCMR3 as having a high prevalence of PFAS in municipal drinking water (n = 5);[32] Criteria 3 and 4—Popular national U.S. beers (Criteria 3; n = 5) and international beers (Criteria 4; n = 3) that are available in U.S. stores (Figure 2). We purchased 23 canned beer types in North Carolina stores in August 2021, with most of the beer purchases having at least 5 different cans of the same beer. Some beers are brewed in multiple locations; thus we confirmed brewing location for the purchased cans based on the brewery can code.

2.2. Analytical Methods. An analytical method was developed for analyzing long- and short-chain PFAS compounds in beer by modifying U.S. EPA Method 533 for measuring PFAS in drinking water.[44−51] Briefly, beer cans were opened and degassed overnight, followed by a 30 min sonication. An aliquot of 40 mL from each beer can sampled was diluted 1:1 with methanol and reserved for analysis. PFAS were measured in beer using solid-phase extraction combined with liquid chromatography-tandem mass spectrometry (LC−MS/MS), with detections performed using negative electrospray ionization and scheduled multiple reaction monitoring. Concentrations of each compound represent the sum of branched and linear isomers, where appropriate. Due to analytical challenges including matrix effects and interferences, the resolution needed for detection and quantification of several PFAS from Method 533 was not able to be achieved with beer. Therefore, only 17 PFAS were considered in this study. The method reporting limit (MRL) was the lowest level of quantification using beer samples spiked with the EPA Method 533 standard mix. The method detection limit (MDL) was the standard deviation of method blanks multiplied by the Student's t value. Additional analytical method information, including a section describing the study's quality assurance and quality control, is in the Supporting Information in Section S1. A tiered analysis approach was used for this study to prioritize method development and then also evaluate intrabeer variability. Overall, 19 beers (19 aliquots—1 from each beer) were analyzed during Phase 1, and 15 beers (75 aliquots—5 from each beer, using 5 different cans of the same beer

Table 1. Summary of PFAS (ppt) in all Aliquots (n = 75) of Phase 2 Beers (n = 15), Where 5 Aliquots Were Analyzed from Each Beer, Including MDL and Method Reporting Limits (MRL)[a]

abbreviation	chemical name	CASRN	chain length	MDL	MRL	detection n > MDL	detection rate (%)	min	mean	median	max
perfluoroalkyl carboxylic acids (PFCA)											
PFHxA	perfluorohexanoic acid	307-24-4	5	1.732	6.563	10	13	5.434	6.136	6.096	6.825
PFHpA	perfluoroheptanoic acid	375-85-9	6	18.367	65.625	0	0				
PFOA	perfluorooctanoic acid	335-67-1	8	2.124	6.563	27	36	2.258	4.645	4.095	8.374
PFNA	perfluorononanoic acid	375-95-1	8	2.112	6.563	2	5	3.163	8.22	5.742	18.231
PFDA	perfluorodecanoic acid	335-76-2	9	2.229	6.563	2	3	3.084	4.824	4.824	6.563
PFUnA	perfluoroundecanoic acid	2058-94-8	11	1.572	6.563	4	5	1.811	4.403	3.321	9.161
PFDoA	perfluorododecanoic acid	307-55-1	12	2.054	6.563	2	3	2.271	2.835	2.835	3.399
perfluoroalkyl ether carboxylic acids (PFECA)											
PFMBA	perfluoro-4-methoxybutanoic acid	863,090-89-5	4	1.365	6.563	7	9	2.494	8.477	7.599	19.911
HFPO−DA	hexafluoropropylene oxide dimer acid	13,252-13-6	5	1.296	6.563	5	7	2.861	3.378	3.255	4.016
perfluorosulfonic acids (PFSA)											
PFBS	perfluorobutanesulfonic acid	375-73-5	4	1.034	5.775	40	53	1.040	4.080	1.669	15.131
PFHxS	perfluorohexanesulfonic acid	355-46-4	6	1.652	11.970	35	47	1.676	3.302	2.633	6.607
PFOS	perfluorooctanesulfonic acid	1763-23-1	8	0.547	6.090	63	84	0.548	1.404	0.901	8.343
fluorotelemer sulfonic acids (FTSA)											
4:2 FTS	1*H*,1*H*, 2*H*, 2*H*-perfluorohexanesulfonic acid	757,124-72-4	6	0.827	6.156	0	0				
6:2 FTS	1*H*,1*H*, 2*H*, 2*H*-perfluorooctanesulfonic acid	27,619-97-2	8	1.287	6.248	5	7	1.812	1.864	1.849	1.937
8:2 FTS	1*H*,1*H*, 2*H*, 2*H*-perfluorodecanesulfonic acid	39,108-34-4	10	1.157	6.300	0	0				
perfluoroalkyl ether sulfonic acids (PFESA)											
PFEESA	perfluoro(2-ethoxyethane)sulfonic acid	113,507-82-7		1.781	11.708	0	0				
9Cl-PF3ONS	9-chlorohexadecafluoro-3-oxanonane-1-sulfonic acid	73,606-19-6		0.709	6.129	1	1	0.748	0.748	0.748	0.748
∑PFAS						71	95	0	9.415	6.782	**40.077**

[a]Selected beer types were brewed in seven North Carolina counties with PFAS in drinking water supplies (Criteria 1, n = 10), two Michigan counties, a Colorado county, and two California counties with PFAS in drinking water supplies (Criteria 2, n = 5). Additional popular national beers were brewed in Massachusetts, Pennsylvania, Wisconsin, Missouri, and Colorado (Criteria 3, n = 5), and international beers were brewed in Holland or two areas of Mexico (Criteria 4, n = 3) (Figure 2).

whenever possible) were analyzed during Phase 2. Ninety-four aliquots were analyzed in total during the study.

2.3. Statistical Methods. ∑PFAS was calculated for each beer as the sum of all PFAS measurements above the MDL. PFAS compounds and ∑PFAS were averaged across the 5 replicate measurements for each beer type, where non-detects in an aliquot were substituted with zero for averaging. Beer names were anonymized for reporting, but the county and state in which each beer was brewed were recorded for spatial data analyses. State-reported PFAS data from drinking water systems in North Carolina, Michigan, and California were used, retaining only the 17 PFAS values measured in beer. Sampling data ranged from 2018 to 2021, averaged to the county level. Brewery locations were matched to state data by the county. To investigate the association between PFAS in beers compared to PFAS in municipal drinking water where beers were brewed, Pearson correlations (r) from the stats package in R were performed for ΣPFAS and individual PFAS. Due to small sample sizes where the same PFAS species were detected or reported in both media (n = 13) and lack of heteroscedasticity in the data, ANOVAs and other statistical tests were not conducted to test for statistical significance. An odds ratio was calculated using the Wald method in the epitools package in R[52] to determine the likelihood of one or more PFAS being detected in beers that were selected for this study based on their proximity to high levels of PFAS in drinking water versus popular national and international beers.

All statistical calculations were performed in R (version 4.4.1).[53] Additional statistical method information can be found in Suppoting Information in Section S2.

3. RESULTS

Using our modified analytical method for determining the presence and concentration of PFAS in beer by adapting EPA Method 533, we matched laboratory analytical results for beer with publicly available data on PFAS within local drinking water by brewing location to characterize the likelihood of inadvertently consuming PFAS when imbibing a beer. PFAS occurrence in beer and local drinking water is described in 3.1 and 3.2, respectively.

3.1. PFAS Occurrence in Beer. *3.1.1. Phase 1 Screening Results.* During Phase 1, where one aliquot from each beer was taken and analyzed, PFAS were detected (above the MRL) in 11 of the 19 beers analyzed. The domestic beers brewed in areas with elevated concentrations of PFAS in drinking water (in NC, CA, and MI) had detections of at least one PFAS in 80% of beers (n = 8/10; Table S4). PFHxA and PFOA were the most detected PFAS in beers from these states. One of the five popular national beers and one of three international beers contained detectable PFAS.

3.1.2. Phase 2 Replicate Results—PFAS Detections. During Phase 2, 5 aliquots were analyzed from each of the 15 beers (1 aliquot from 5 different cans of the same beer whenever possible) to analyze each beer in replicate, address

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intrabeer variability, and obtain a more robust data set. One or more PFAS were detected above the MDL in 95% (71 aliquots) from 13 of the 15 beers (Table 1). The largest number of PFAS compounds were detected in beer aliquots from Chatham County, NC (PFHxA, PFOA, PFMBA, PFBS, PFHxS, and PFOS), and Mecklenburg County, NC (both areas with PFAS in municipal drinking water), and a beer from St. Louis County, MO (Table S5). The most detected PFAS in beer aliquots were PFSAs—PFOS, PFBS, and PFHxS [84% (n = 63), 53% (n = 40), and 47% (n = 35), respectively] (Table 1). PFOA was also detected in 36% (n = 27) of beer aliquots (Table 1), while PFEESA was not detected in any beer aliquots and only one aliquot had detectable 9Cl-PF3ONS. 6:2 FTS was only detected in aliquots from one New Hanover County, NC beer and HFPO−DA from another New Hanover County, NC beer. Criteria 1 beers from North Carolina (selected because of PFAS in municipal drinking water), particularly those within the Cape Fear River Basin, generally had more detectable PFAS compounds than Criteria 2 beers from Michigan or California that were also selected due to PFAS in localized municipal water. Aliquots from half of NC beers (n = 3 of 6) and 75% of Criteria 2 beers (n = 3 of 4) contained detectable levels of PFOA. PFOS was detected in most aliquots from all beers analyzed during Phase 2.

3.1.3. Phase 2 Replicate Results—Highest PFAS Concentrations in Individual Samples. The highest PFAS concentrations measured in beer aliquots were PFMBA (19.911 ppt), PFNA (18.231 ppt), and PFBS (15.131 ppt) from Criteria 1 and 2 beers from Chatham County NC, Mecklenburg County NC, and Kent County MI, respectively (Table S5). The highest concentrations for each targeted PFAS compound, including PFMBA, PFNA, PFHxA, PFDA, PFUnA, HFPO−DA, PFHxS, and PFOS, were predominantly from Criteria 1 NC beers (Table S5), though a Criteria 2 beer sample from Kalamazoo County, MI, had the highest concentration of PFOA (8.374 ppt). The highest ∑PFAS concentration (40.077 ppt) was from a Mecklenburg County, NC Criteria 1 beer aliquot, and all five aliquots from a Chatham County, NC Criteria 1 beer had ∑PFAS concentrations of >30 ppt (Table S5).

3.1.4. Phase 2 Replicate Results—Highest Mean PFAS Concentrations. Overall, the beers with the highest mean concentrations (average of 5 replicate aliquots above the MDL) were PFBS, PFHxS, and PFOS (9.538 6.253, and 6.207 ppt, respectively) from Criteria 1 North Carolina beers (Table S6). The beer with the highest mean concentration of PFOA (6.618 ppt) was a Criteria 2 beer from Kalamazoo County, MI (Table S6). The highest averaged ∑PFAS concentrations were measured in Criteria 1 beers from Chatham County, NC (33.946 ppt) and Alamance County, NC (21.536 ppt) (Figure 3). Average ∑PFAS concentrations of Criteria 3 and 4 beers (popular national and international beers) were similar to the average ∑PFAS concentrations of many Criteria 1 and 2 beers. Criteria 1 and 2 beers were selected based on their brewery locations' proximity to elevated drinking water PFAS levels (Figure 3), while Criteria 3 and 4 beers were initially intended to act as controls.

3.1.5. Phase 2 Replicate Results—Variability. More than one PFAS compound was detected in most beers. For PFAS that were detected in two or more beers (PFHxA, PFOA, PFBS, PFHxS, and PFOS), the lowest variability between replicate aliquot measurements of the same beers (5 aliquots of the same beer from 5 different cans whenever possible) was observed for PFHxA and PFHxS (SD < 15%; Table S5). For PFOA and PFOS, standard deviations ranged from 14%−63% and 7%−51%, respectively, while PFBS exhibited the highest variability (SD ranged from 12%−182% for 5 aliquot analyses of the same beers). Among beers, three or more PFAS detected (Table S6), two beers showed consistent replicate measurements with standard deviations below 30% of the mean (Figure 4).

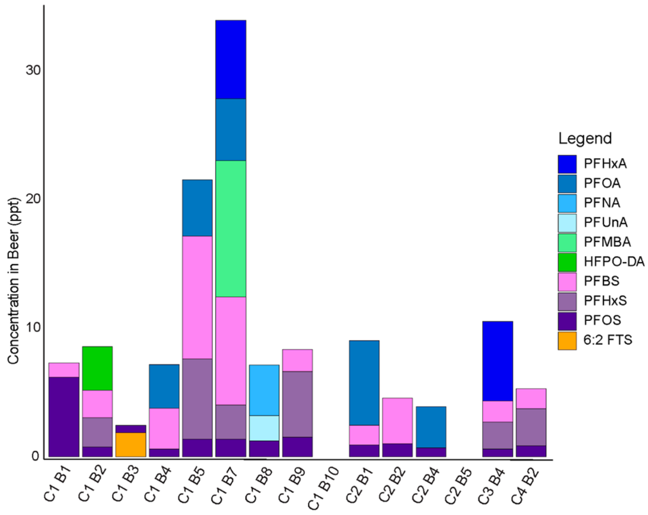

Figure 3. Stacked barplots showing averaged replicate concentrations (average of 5 aliquots per beer; ppt) for PFAS identified in anonymized beers during Phase 2 analyses (**C**riteria #, **B**eer #; additional information in Table S66). Only PFAS with averaged concentrations above their MDLs are shown.

3.2. PFAS in Local Drinking Water. County-level spatial analyses of ∑PFAS data from public water systems drinking water showed geographic variability among the three states where Criteria 1 and Criteria 2 beers were brewed (Figure 5). Michigan counties generally had lower ∑PFAS levels in drinking water than were observed in North Carolina and California. Within North Carolina, higher ∑PFAS concentrations were observed in drinking water in counties within the Cape Fear River Basin.

Similar geographic trends were observed with replicate-averaged ∑PFAS concentrations in beers, as were observed in the drinking water, with the highest ∑PFAS concentrations in both beer and drinking water identified within the Cape Fear River Basin in North Carolina (Figure 5). However, variation was observed in the types of PFAS detected and the concentrations of PFAS measured in North Carolina, where for example replicate-averaged ∑PFAS ranged from 2.444 to 8.568 ppt within four beers brewed in New Hanover County (Table S6). Replicate-averaged ∑PFAS, PFOA, and PFBS beer concentrations in particular were strongly and positively correlated with averaged drinking water concentrations (Table S7) from the counties where they were brewed (r = 0.82, 0.90, and 0.71, respectively), but not for PFOS (r = −0.09) (Figure S1).

4. DISCUSSION

Research studies increasingly indicate that PFAS are pervasive in drinking water supplies,[28,54,55] foods,[56] and beverages, emanating from their manufacture, market demand,[57] consumer product use,[58] and resistance to degradation.[17] Drinking water plays an integral role in the beer brewing process. The

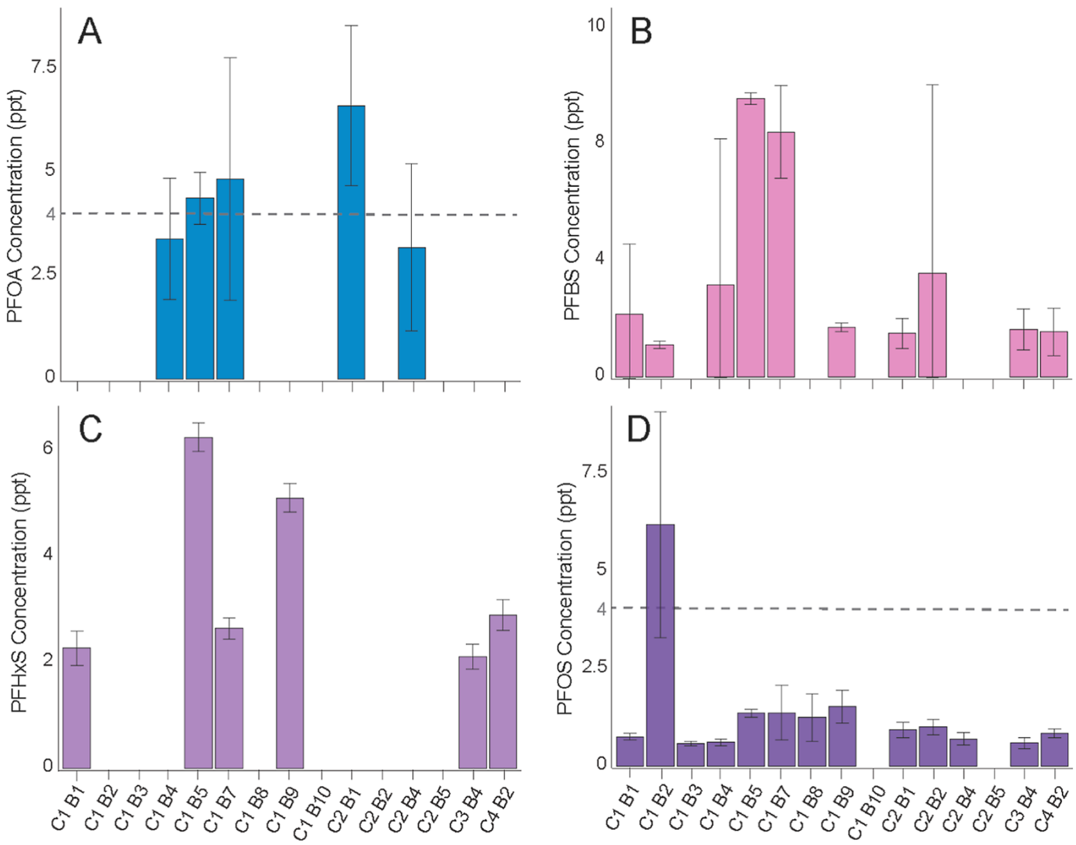

Figure 4. Barplots showing averaged replicate (A) PFOA, (B) PFBS, (C) PFHxS, and (D) PFOS concentrations (average of 5 aliquots per beer; ppt) in beer from replicate analyses (Criteria #, Beer #, additional information in Table S66). Error bars indicate standard deviations and dashed gray lines indicate U.S. EPA's MCL for PFOA and PFOS (US EPA 2024). Only averaged concentrations above each PFAS MDL are shown.

water used introduces potential contaminants during several beer production steps, where as much as 7 L of water is used to produce 1 L of beer[11] (see Supporting Information for brewing process). By adapting EPA Method 533 to analyze PFAS in beers sold in U.S. retail stores, we found that PFAS in beer correlates with the types and concentration of PFAS present in municipal drinking water used in brewing. We detected PFAS in most aliquots of beer, highlighting the prevalence of PFAS in water supplies and its impact on water-based beverages like beer. Our findings indicate a strong link between PFAS in drinking water and beer, with beers brewed in areas with higher PFAS in local drinking water translating to higher levels of PFAS in beer, showing that drinking water is a primary route of PFAS contamination in beer. In this section, we discuss PFAS occurrence in beer, the most common PFAS, and compare other studies on PFAS in beverages and drinking water.

4.1. PFAS Occurrence in Beer. *4.1.1. Pervasive Contaminant with Variability from Can to Can.* At least one PFAS was detected in almost all beers analyzed, indicating that PFAS in beer is a global concern. Additionally, the presence of PFAS in beer is not limited only to areas around known contaminated sites and is linked to PFAS in public water supplies, showing the downstream effect on water-based beverages including beer. We also found that within one six pack, the PFAS levels varied some from can to can.

4.1.2. Lingering Presence. Although the use of longer chain PFAS like PFOA and PFOS have been reduced since the 2000s, their presence in the environment continues to be evident in the beers analyzed in our study and others.[56] PFOA has also been shown to damage yeast cells, which could weaken fermentation during the brewing process;[59] thus this legacy PFAS could also impact brewing efficiency.

4.1.3. Most Common PFAS—A Connection to Firefighting Foam. PFSAs were the most common PFAS among the beers analyzed. PFSAs pose greater health risks due to their increased bioaccumulation compared to PFCAs, especially the longer chain compounds.[60] For example, PFOS and PFHxS have been found at higher concentrations in areas proximal to AFFF firefighting foam use at military bases, airports, and fire training sites.[61] The high incidence of PFOS in the beer aliquots suggest that a primary source of PFAS contamination in beer can also be attributed to current or past AFFF pollution of the environment, though they can also be linked to other industrial processes.[61] PFBS has become a prominent industry alternative to PFOS due to its shorter chain length and was also found in many aliquots of the beers, potentially showing the transition of regional sources to these new PFAS species.

While shorter chain length generally indicates less bioaccumulation, in vivo studies do not agree about the level of toxicity or potential for adverse health effects compared to the longer chain PFAS.[62,63] PFBS is still highly stable and mobile in the environment, so extensive use as replacements could present contamination and exposure concerns similar to legacy PFAS.[62−64] The n:2 FTSAs were generally not detectable in study beers, except for 6:2 FTS detected in one NC beer. As FTSAs have replaced legacy PFAS in some AFFF formulas, this detection could indicate more recent AFFF use nearby. These chemicals can also be aerobically biotrans-

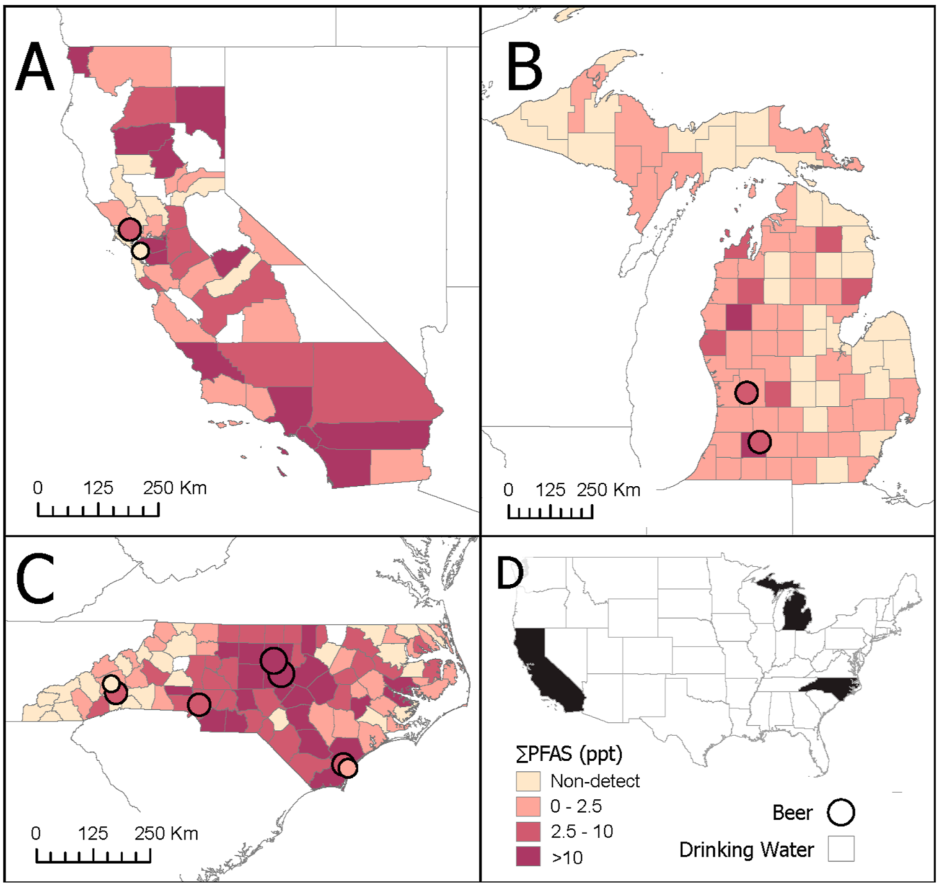

Figure 5. Maps showing county-averaged ∑PFAS concentrations (ppt; gray outlined polygons with color scale) from state-reported drinking water systems in (A) California, (B) Michigan, and (C) North Carolina, along with replicate averaged∑PFAS concentrations in beers at brewing locations (ppt; color scale within bold outlined circles). Map D shows locations of states in A-C within United States.

formed into PFCAs which may explain the lack of other detections of n:2 FTSAs in the beers.[65]

4.2. Comparison to Other Studies on PFAS in Beer.

To our knowledge, only one prior study conducted a limited evaluation on PFAS in beer.[10] Our study adapted updated analytical methods to evaluate a greater number of PFAS (17 instead of 11) and compared the spatial extent of beers to municipal water data within brewing locations. We evaluated beers from multiple counties (17), states (9), and countries (3), compared to the other study only including three small areas in two neighboring European countries.[10] Of the PFAS detected and measured in both studies (PFOA, PFOS, PFHxA, PFNA, and PFDA), mean concentrations from all study samples were higher from beers in this study (4.645, 6.136, 8.220, and 4.824 ppt, respectively) compared to the previous study (1.82, 4.80, 3.77, and 0.64 ng/L) for all chemicals except PFOS (1.404 ppt in this study versus 4.84 ng/L in previous study). However, PFOS was the most frequently detected chemical found in the beers in both studies. These findings suggest that drinking water contamination from legacy and emerging PFAS continues to be a concern in beers worldwide, even a decade later. Additional information is available in the Supporting Information in Section S4.1.

4.3. Comparison to PFAS Drinking Water Guidelines.

In 2023, the U.S. EPA established MCLs for six individual PFAS and a mixture of several PFAS in drinking water under the National Primary Drinking Water Regulation.[66] While there are currently no standards for PFAS levels in beer, these drinking water standards can provide insight, as beers are intended for direct consumption similar to drinking water. We found that some of the beers exceeded the health standards. Three beers were above the PFOA MCL (4 ppt)—two beers from the upper Cape Fear River Basin in NC and one beer from Michigan, and one beer in the lower Cape Fear River Basin of NC exceeded the PFOS MCL (4 ppt) (Table S6 and Figure 4; replicate-averaged). Several other beers also had individual (but not replicate-averaged) aliquots with PFOA and PFNA (10 ppt) above their MCLs, while 14 other beers had detectable levels of PFHxS, PFNA, or HFPO−DA below their MCLs (10 ppt). The hazard index for mixtures of PFNA, PFHxS, PFBS, and HFPO−DA were not exceeded, and the remaining 11 PFAS compounds analyzed in our study do not currently have U.S. drinking water standards for comparison.

4.4. PFAS in Beer and Drinking Water Occurrence.

Beers selected based on their brewery location's proximity to known elevated levels of PFAS in drinking water had 15 times the odds of having one or more detection of PFAS compared to larger-scale U.S. or international beers selected based on consumer popularity without known PFAS sources in municipal water. The PFSAs and PFOA had the highest detection rates and were also among the most frequently detected chemicals in drinking water across the United States in recent studies.[26,28,55,67] The substitution of long-chain PFSAs with short-chain PFSAs (PFBS) has also been observed with high detection rates in recent drinking water studies as well as beers we analyzed.[26,28,55,61]

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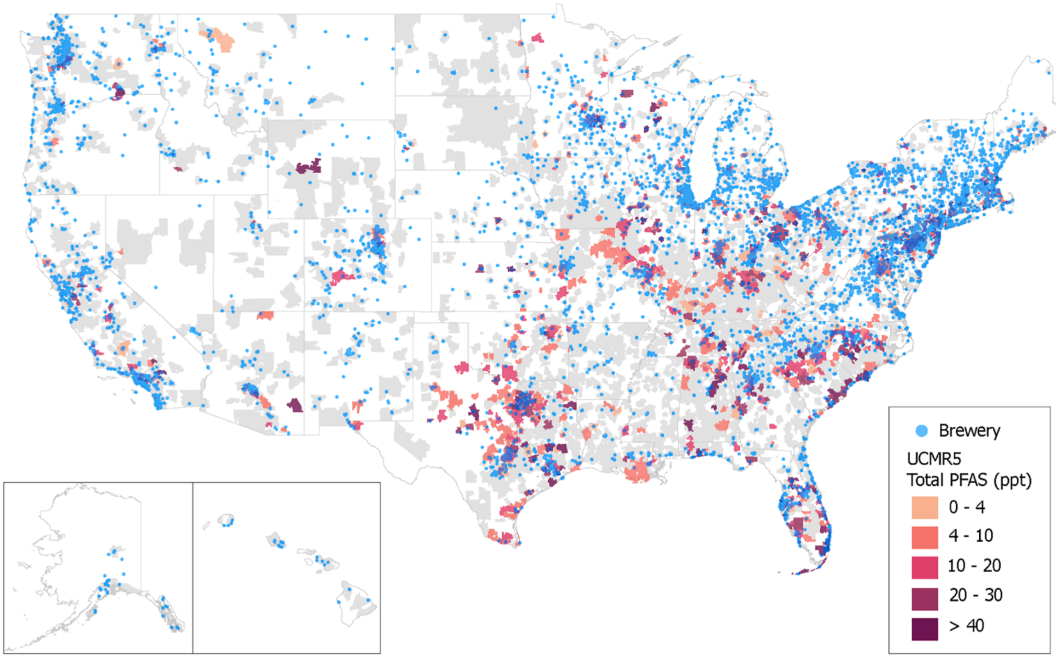

Figure 6. U.S. Map showing total PFAS (ppt; color scale) in zip codes served by public drinking water supplies reported by UCMR5 (July 2024) and locations of currently operating breweries (light blue circles). See Figure S2 for additional maps zoomed into several regions.

North Carolina beers, particularly those within the Cape Fear River Basin, generally had detections of more PFAS species than Michigan or California beers, which reflects the variety of PFAS sources in NC.[68] The two beers with the largest number of different PFAS detected were both located in the upper regions of the Cape Fear River Basin in Chatham and Alamance counties, where larger variability in the types of PFAS as well as higher concentrations of PFAS have been observed in surface waters in the Haw River.[14,68] HFPO−DA was detected in both beer and raw water from a drinking water treatment plant (DWTP) in the lower region of the Cape Fear River Basin.[14] The DWTP at which HFPO−DA was detected pulls in water from the Cape Fear River downstream from a fluorochemical manufacturing plant that produces the chemical.[14,69]

Similarities between PFAS in drinking water and beer were also observed in Michigan, where Kalamazoo County had the highest reported average PFOA concentration from the state-reported drinking water of all counties in the three states. The beer brewed in this county also had the highest measured PFOA concentration of all of the beers in the study. The correlations between $\sum$PFAS, PFOA, and PFBS levels in beers were linked to local drinking water contamination.

Approximately 18% of breweries operating in the United States are located within zip codes served by public water supplies with detectable PFAS in drinking water as reported by UCMR5 (as of July 2024; Figures 6 and S2). We found that international beers were less likely to have detectable PFAS or PFAS at higher levels, which may reflect the lack of or lower levels of PFAS in drinking water in these regions. The first study of PFAS in tap water in Latin America found that PFAS were not generally associated with any drinking water source in Guatemala City, the region's largest city, which lacked PFAS manufacturing industries; rather, PFAS occurrence in tap water was instead associated with plastic water storage tank usage.[70]

While PFAS detections and concentrations were elevated in beers in NC, CA, and MI with known PFAS in water, PFAS was also detected in some national and international beers selected for this study, revealing that PFAS exposure in beer is a concern for a wide variety of beers.

4.5. Water Treatment. Water quality and water filtering are important aspects of brewing beer to ensure proper water chemistry for taste, efficiency, and avoidance of scaling and corrosion.[12,71] Pretreatment typically consists of filtering to remove particles and turbidity plus pathogen disinfection for consumer safety. The effectiveness of PFAS removal in drinking water varies by the treatment method and chemical. Activated carbon filtration, ion exchange, and reverse osmosis are treatment techniques that can be used to prepare water for brewing.

Conventional water treatment employed at municipal drinking water treatment plants have been shown to be nearly ineffective at removing PFAS.[72,73] This can leave the burden and cost of implementing more sophisticated water treatments to brewers unless public water suppliers implement tertiary treatment to remove PFAS from finished water prior to distribution. Anion exchange and activated carbon treatments have been shown to more effectively remove longer-chain PFAS and PFSAs but were less effective in removing PFCAS and the alternative shorter-chain PFAS and PFECAs.[14,72] Reverse osmosis treatment showed significant removal of PFAS of different chain lengths in drinking water, but can be prohibitive due to high operational costs and energy usage.[73] In areas with known contamination, beers from macro-breweries were less likely to have detectable PFAS than craft beers brewed at a smaller scale, potentially due to more effective and expensive filtration of tap water at larger breweries (additional information in Supporting Information in Section S4.2).

4.6. Limitations. Our study aimed to modify a widely used analytical method to detect PFAS in beer, characterize its presence, and determine whether PFAS in local drinking water influenced PFAS measured in beer. Future innovations in analytical methods for measuring PFAS in this matrix could

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lead to increased sensitivity for detecting the PFAS reported here as well as include detections of the remaining PFAS from Method 533. Variability in PFAS in several beers from the same county in North Carolina points to hyperlocal factors affecting PFAS contamination in beers either within drinking water quality, within the brewing processes of each beer, or temporally. These findings could be due to PFAS introduced into beer from sources other than water, such as the ingredients used in different recipes and the brewing equipment used. Packaging vessels such as bottles, cans, and kegs may also be washed with water or contain liners that could also introduce PFAS postbrewing. We did not sample other inputs to beer such as hops or onsite facility testing of storage tanks, and limited our sampling to cans. Specific source waters and filtration methods used for brewing each beer were also unknown and were not tested during this study.

There were also no distinct patterns apparent in the detection rates for PFAS with varying chain lengths for the beers analyzed in this study, even though that property has been shown to affect the solubility and vaporization of these compounds.[74] Given the difficulty in cleaning laboratory equipment with darker beers, these were not evaluated. We analyzed 22 brands of beer in total (selecting a lighter version for each brand). While beers were initially removed from further analysis after not having PFAS detections during Phase 1, the variability between replicate aliquots from the same beers in Phase 2 indicated that the discarded beers could still potentially contain PFAS. While the geographic reach of beers analyzed in this study improves upon that from the previous study of PFAS in beer, it still represents a limited sample size and geographical distribution of PFAS measurements in beers and municipal drinking water that could be expanded upon in future work for a more robust statistical analysis. Additional information is in Supporting Information in Section S4.3.

4.7. Possible Actions Available and Future Research Needs. *4.7.1. For Brewers and Consumers.* We identified spatial parallels between PFAS levels in local drinking water and beer that indicate that drinking water is a primary route of PFAS contamination in beer. This finding provides breweries, particularly smaller craft breweries, an opportunity to ensure that their water filtration methods are adequately removing PFAS from source water, especially in areas with known PFAS. Brewers can check their public water utility results or test their water, and if PFAS are present, install activated carbon or reverse osmosis water filtration to remove PFAS-contaminated water being added to the brewing process.[14,72,73,75] Additionally, consumers can check where beers are brewed and make more informed decisions regarding their purchases and consumption habits to reduce overall PFAS exposure.

4.7.2. Data-Driven Decision Making. As the first study of PFAS in beer with varying company sizes and brewing locations globally, the results expand our understanding of the pervasiveness of PFAS in consumable beverages and pave the way for additional research, policy planning, and advancements in water quality and food safety for governmental agencies, utilities, and policymakers.

4.7.3. Future Research. Future studies with additional resources could further identify exposure risks by analyzing a larger sample size of beers and other beverages with replicates to characterize PFAS concentrations and variability between brands in bottled, canned, and bulk forms and also evaluate additional PFAS sources such as packaging materials. Additionally, associations between PFAS and types of beers (e.g., lagers, ales, etc.) could be investigated to determine whether some beer recipes introduce different compositions or levels of PFAS.

Additionally, as beer alternatives such as spiked seltzers are becoming increasingly popular, analytical methods could be further refined to test more beers and other beverages from different regions and compare patterns of PFAS groups or chain lengths.[28,55] Increased understanding of PFAS presence and sources will ultimately help to inform brewers, consumers, and policymakers in making data-driven decisions about beer consumption and address risks. Additional information is in the Supporting Information in Section S4.3.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c11265.

> Additional text and tables with analytical method information; tables showing all PFAS measurement results for beers tested during Phase 1 and Phase 2 analyses; table summarizing PFAS measured in municipal waters by county; figure showing relationship between PFAS in municipal waters and beers; additional text describing statistical analyses, beer brewing processes, comparison between this study and previous study on PFAS in beer, current water treatment for PFAS in a county in this study, study limitations, and future research needs; and figure showing zoomed in areas from Figure 6 (PDF)

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Notes

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