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Association Between Serum Levels of Perfluoroalkyl and Polyfluoroalkyl Substances and Dental Floss Use: The Double-Edged Sword of Dental Floss Use—A Cross-Sectional Study

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ABSTRACT

Background: Although evidence suggests that dental floss contains perfluoroalkyl and polyfluoroalkyl substances (PFASs), it is still uncertain whether the use of dental floss contributes to an increased risk of PFAS exposure.

Methods: We analysed data on serum PFAS concentrations and dental floss usage in a cohort of 6750 adults who participated in the National Health and Nutrition Examination Survey (NHANES) from 2009 to 2020. In our study, we used logistic regression, a survey-weighted linear model, item response theory (IRT) scores, inverse probability weights (IPWs) and sensitivity analysis to assess the potential impact of dental floss usage on human serum PFAS levels.

Results: The analysis of six PFASs revealed that dental floss users had higher serum concentrations of perfluorooctanoic acid (PFOA) compared with non-users, while serum concentrations of other PFASs were lower. Dental floss users recorded a lower level of overall PFAS burden score compared with non-users. Sensitivity analysis showed a statistically significant increase in serum PFOA concentration among dental floss users.

Conclusion: Our findings suggest that the use of dental floss may be associated differently with serum concentrations of specific PFASs. Among a large representative sample of U.S. adults, individuals reporting the use of dental floss had lower levels of serum PFASs overall, with the exception of PFOA, which was slightly elevated. Dental floss is an important oral hygiene tool, and further research is needed to clarify its role in PFAS exposure.

1 | Introduction

Perfluoroalkyl and polyfluoroalkyl substances (PFASs) are a large group of synthetic chemicals known for their persistence in the environment and their widespread use in various industrial and consumer products. Over the past seven decades, the industrial use of PFASs has expanded to more than 200 applications and over 4000 individual PFAS compounds, with further expansion ongoing (Evich et al. 2022; Gluge et al. 2020; Wang et al. 2021). The widespread use of PFASs in industrial applications and the stability of their degradation products have resulted in their extensive presence in the environment (Ankley et al. 2021). Studies have shown that in developed countries, almost the entire population has measurable PFASs in their blood (Stubleski et al. 2016; Zheng, Eick, and Salamova 2023). PFAS compounds are used for their non-sticking, grease-resistant and water-resistant properties, which make them valuable in various industries, including cookware, clothing and food packaging. For the general population, personal household items such as cleaning products and some medical devices may serve as pathways for exposure to PFASs (Evich et al. 2022; Holder et al. 2024; Kim, Lee, and Oh 2019). Owing to the extended half-life of PFASs and the detection of these compounds in human organisms, medical and scientific communities have shown great concern about the effects of PFASs on human health (National Academies of Sciences and Medicine 2022). Many studies have reported that exposure to PFASs can result in adverse effects on human health, and these effects are multifaceted. When PFASs enter the body, they can accumulate in human liver and kidney tissues. This accumulation can lead to damage of liver cells, non-alcoholic fatty liver disease and an increased incidence of kidney cancer (Armstrong and Guo 2019; Nian et al. 2019; Stanifer et al. 2018). In addition to accumulating in liver and kidney tissues, PFASs may have a tumour-promoting effect on the development of thyroid cancer (Coperchini et al. 2024). PFASs can also impact children, and studies have shown that PFASs can increase the risk of rhinitis and respiratory infections in children by suppressing their immune response (Kvalem et al. 2020). Furthermore, studies have found that PFASs may have an impact on human sex hormones and female reproductive health (Ding et al. 2020; Rickard, Rizvi, and Fenton 2022). The toxic effects of PFASs on humans may be related to the weakened function of the human immune system, oxidative stress and endocrine disorders. PFASs can enter the human body through a variety of ways, including via diet, drinks and inhalation. Once inside the human body, they accumulate and become distributed in the blood, liver, kidney, brain and other human organs (Manojkumar et al. 2023). Oral ingestion may be the main route for PFASs to enter the human body, including via contaminated water and food (Boone et al. 2019; Curtzwiler et al. 2021). Additionally, personal care products may be an important means of increasing the overall intake of PFASs. Some dental products, such as dental floss, may contribute to increased PFAS intake due to long-term exposure in the mouth.

Dental floss has become widely accepted as an aid for cleaning the surfaces of teeth and preventing dental caries and periodontal disease in daily life (Marinho et al. 2003). It is usually made from materials such as nylon thread, silk thread, PTFE (polytetrafluoroethylene, a type of fluoropolymer) or other substances and is usually coated uniformly with wax. Certain types of dental floss may use specific PFASs. For example, Oral B Glide floss is made from 100% PTFE rather than being merely coated with PFASs. This is supported by multiple sources, including statements from Procter & Gamble and studies that have identified the presence of fluorine in Oral B Glide, confirming the use of PFAS-related materials such as PTFE. While Oral B Glide and similar products are manufactured with PTFE, it is important to note that other types of dental floss may also contain PFAS-based coatings or materials. Some studies have found detectable levels of fluorine in several dental floss products, including both PTFE and non-PTFE flosses, suggesting that other types of floss may use PFAS-based coatings (Boronow et al. 2019). The physical properties of PTFE dental floss are more favoured by users (Huang, Broadbent, and Choi 2023). However, the prevalence of PFAS-containing dental floss in the market remains somewhat unclear, as certain brands have moved toward PFAS-free alternatives in response to growing consumer concerns.

The unique characteristics of PFASs cause them to accumulate in the human body, and this accumulation can lead to adverse health outcomes. To protect public health, it is important to assess the potential risk of users being exposed to PFASs. Studies have shown that educational efforts aimed at reducing PFAS exposure have resulted in behavioural changes, such as decreased use of non-stick cookware and dental floss containing PFASs (Boronow et al. 2023). However, lack of education may inadvertently result in the continued use of dental floss containing PFASs and subsequent potential exposure risks. A study on 178 middle-aged American women indicated that participants who used Oral B Glide dental floss recorded higher levels of serum PFHxS (Boronow et al. 2019). This suggests that the use of specific types of dental floss may contribute to accidental PFAS exposure; however, the study had a limited sample size. Therefore, it is important to study whether the use of dental floss can increase the risk of PFAS exposure.

The aim of this study was to investigate the potential correlation between dental floss usage and serum levels of PFASs in the human body. In our study, we assessed the serum levels of PFASs in a cohort of adults in the United States by analysing data from the National Health and Nutrition Examination Survey (NHANES). Then, we used the results to compare serum levels of PFASs in people who use dental floss with those who do not.

2 | Materials and Methods

2.1 | Study Population

The data for this study were obtained from NHANES, a nationally recognized, continuous, cross-sectional survey conducted by the Centers for Disease Control and Prevention (CDC) and the National Center for Health Statistics (NCHS). Its primary goal is to collect comprehensive data on the nutritional and health status of the population in the United States. Our study used NHANES data from 2009 to 2020, which included information on PFAS concentrations and dental floss usage. We included all eligible participants from the relevant NHANES cycles to maximize both the sample size and the robustness of our findings. A total of 55,999 participants were eligible for our analysis. According to the NHANES survey, the target age range for dental floss usage is 30–150 years; therefore, 28,844 participants younger than 30 years were excluded. We then excluded 20,405 participants with missing key information or covariate information. Ultimately, a total of 6750 participants who fulfilled the eligibility criteria were included in our study. Our analysis was conducted in accordance with NHANES's public use dataset guidelines and used publicly available NHANES data, which does not require additional ethical approval for secondary data analysis. The flow chart in Figure 1 illustrates the process of selecting the study population.

2.2 | Dental Floss Usage Assessment

The dental floss usage status in this study was assessed by studying the answers provided by participants in the NHANES questionnaire, specifically regarding the number of days that they had used dental floss in the past week (range: 0–7 days). Participants were categorized as follows: those who reported using dental floss for 0 days were classified separately from those who used it for 1–7 days. Participants who responded with ‘refused’ or ‘don't know’ or had missing data were excluded from the statistical analysis.

2.3 | Serum Level of PFAS Assessment

The concentration of PFASs in human serum was quantitatively determined using an analysis technique known as solid-phase-extraction high-performance liquid chromatography-turbo spray ionization-tandem mass spectrometry (SPE-HPLC-TSI-MS/MS) (Kuklenyik, Needham, and Calafat 2005). Among the PFAS compounds identified in the NHANES laboratory data, our focus was on those detected in over 50% of the analysed samples. The targeted PFAS compounds included perfluorooctanoic acid (PFOA), perfluorononaic acid (PFNA), perfluorohexane sulfonic acid (PFHSA), perfluorooctanesulfonic acid (PFOSA), perfluorodecanoic acid (PFDA) and 2-(*n*-methyl-perfluoroocta nesulfonamide) acetic acid (MeFOSAA). When the concentrations fell below the lower limit of detection (LLOD), we treated them as binary variables: concentrations below the LLOD were assigned a value of 0 (non-detectable), and detectable levels were assigned a value of 1. This method ensures that compounds with limited detection are appropriately handled without introducing bias.

The overall burden of PFASs among the participants was evaluated through item response theory (IRT) scores. IRT has recently been used to assess biocumulative exposure burden scores for environmental pollutants such as PFASs (Liu et al. 2022). PFASs typically exhibit different patterns of exposure and bioaccumulation. PFAS burden is a composite measure derived from multiple PFASs, with each compound contributing to the overall exposure. Therefore, we applied an IRT model and treated different PFAS ‘items’ to estimate the correlation between each compound and the potential burden of PFAS. The IRT method estimates the relative contribution of each PFAS based on its detection frequency, concentration distribution and overall variability. Compounds with higher mean levels or detection rates (e.g., PFOSA) are weighted more heavily in the calculation of the score, while less frequently detected compounds contribute proportionally less. This approach balances the influence of each analyte and provides a composite measure of PFAS burden that reflects overall exposure. The IRT model estimates the relative position of each participant's latent PFAS burden, with the scores typically centred around a mean of zero. Negative values are a natural outcome of the IRT model and indicate that an individual's latent PFAS burden is below the population average, while positive values indicate above-average burden levels. To enhance clarity and improve the interpretability of the results, we applied a linear transformation to shift all scores into a positive range. This transformation does not alter the relative differences

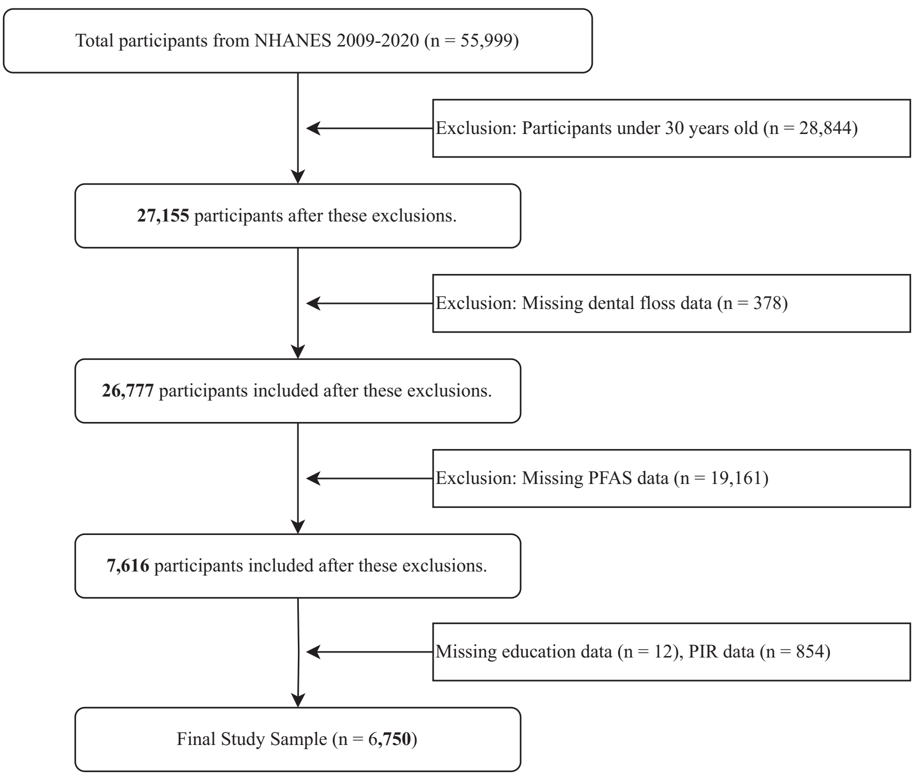

FIGURE 1 | Flowchart of the study.

or statistical significance of the results. IRT enabled us to calculate an overall burden score that reflects the combined influence of multiple PFASs, providing a more nuanced measure of PFAS exposure. This methodology allowed us to consider the variability in detection rates and concentrations across different PFASs, thereby enhancing the precision of our analysis.

For more detailed information on laboratory methods and instruments, refer to the NHANES Laboratory Procedures Manual (https://wwwn.cdc.gov/nchs/data/nhanes/2015-2016/labmethods/PFAS_I_MET.pdf).

2.4 | Covariates

On the basis of the existing NHANES literature on serum PFAS levels, we identified several relevant predefined covariates as potential confounders and incorporated them into our adjusted model. We included participants' sex, age, race/ethnicity, educational attainment, poverty–income ratio (PIR), frequency of recreational activity and NHANES cycle as covariates.

In relation to the covariate of sex (male or female), previous studies have indicated sex-related differences in PFAS metabolism (Jane et al. 2022), and thus it is critical to adjust for this factor to account for variability in PFAS serum concentrations between men and women. Age (a continuous variable) is a known factor influencing PFAS levels because accumulation tends to increase with age. Our model adjusts for this variable to ensure that differences in the PFAS burden are not simply due to differences in the participants' age. Younger participants typically have different behaviours related to oral hygiene, including a lower frequency of usage of dental floss (Hitz Lindenmüller and Lambrecht 2011), and they may also have different PFAS exposure pathways. In relation to the covariate of race/ethnicity (non-Hispanic White, non-Hispanic Black, Mexican American, other races), PFAS exposure patterns can vary by race/ethnicity as a result of differences in lifestyle, dietary habits and environmental factors. Therefore, race/ethnicity was included as a covariate to account for potential differences in PFAS exposure sources across these groups. Education attainment (0–12 grades, high school graduate/GED, some college or above) can be a proxy for socioeconomic status, which in turn may affect environmental exposure and access to products that may contain PFASs. This variable helps in accounting for potential socioeconomic confounders. PIR (<1.3, 1.3–3.5 and ≥ 3.5) can also help address potential confounding by socioeconomic factors, which are known to influence both oral hygiene behaviours (e.g., dental floss use) and PFAS exposure pathways. The covariate of frequency of recreational activity (none, moderate, vigorous or both) was constructed by combining several NHANES variables related to physical activity intensity and duration. Specifically, we categorized participants based on their self-reported engagement in moderate, vigorous or both moderate and vigorous activities, as captured by the NHANES questionnaire on physical activity. These categories were created to reflect different levels of physical activity, with 'moderate and vigorous' representing individuals who engaged in both types of activity, which we hypothesized might reflect more consistent or higher intensity exposure compared with those engaging in only one type. Given that PFASs are used in various recreational products, such as outdoor clothing and sports equipment, the frequency of recreational activity was included to adjust for potential exposure from these sources. PFAS levels vary by NHANES cycle because legacy PFASs are being phased out over time. The demographic information of the participants, including sex, age, race/ethnicity, education attainment, PIR and frequency of recreational activities, was obtained from NHANES's demographic data. All data were collected by trained interviewers. They collected relevant information in participants' homes with the computer-assisted personal interview (CAPI) system.

2.5 | Statistical Analysis

The general differences between individuals who use dental floss and those who do not were examined using survey-weighted chi-square tests. The adjusted geometric mean of individual PFAS concentrations and the adjusted mean of the overall burden score were calculated using a survey-weighted linear model. Corresponding 95% confidence intervals, *p*-values and statistical significance were also determined. Serum PFAS concentrations were compared between groups based on the corresponding results. In this study, we constructed a model with prior knowledge to control confounding factors and make the most appropriate adjustments. Relevant covariates included sex, age, race/ethnicity, education attainment, PIR, NHANES cycle and frequency of recreational activity (considered as a potential risk factor for increased PFAS exposure due to the use of related products in recreational activities such as sports equipment, outdoor clothing and climbing ropes [Gluge et al. 2020]).

The distribution of PFAS concentrations in human serum was revealed through density and cumulative distribution plots. Box plots and violin plots were used to further demonstrate the distribution of PFAS concentrations. The constructed linear model accounted for confounding factors by using inverse probability weights (IPWs). IPWs adjust for the likelihood of using dental floss based on participant characteristics (age, sex, etc.), ensuring that the sample is representative of the population. Additionally, a logistic regression model was established to classify the binary results based on the predictors, and robustness of the estimated IPWs has been demonstrated (Zalla et al. 2022). The data analysis was performed using R software (v. 4.4.0) and the packages *survey*, *gtsummary* and *mirt*. These packages were essential for conducting the survey-weighted analyses, which properly account for NHANES's complex survey design. All statistical tests were conducted using a two-tailed approach, and a *p*-value <0.05 was considered statistically significant.

3 | Results

3.1 | Study Population Characteristics

In total, 6750 participants were eligible for our analysis. The general characteristics of participants who do or do not use dental floss are summarized in Table 1. Among the participants, 4384 (64.95%) reported using dental floss, while 2366 (35.05%) did not. Of these, 1914 male and 2470 female individuals were in the dental floss user group, compared with 1330 male and 1036 female individuals in the dental floss non-user group. However,

TABLE 1 | General characteristics of study population participants in the National Health and Nutrition Examination Survey, 2009–2020.

Characteristics, *n* (%)	Total ($n = 6750$)	Dental floss No ($n = 2366$)	Dental floss Yes ($n = 4384$)	*p**
Sex				< 0.0001
Male	3244 (48.01)	1330 (57.01)	1914 (44.23)	
Female	3506 (51.99)	1036 (42.99)	2470 (55.77)	
Age group				0.001
< 40 years	1364 (22.22)	441 (23.07)	923 (21.86)	
40–50 years	1399 (22.63)	421 (20.11)	978 (23.68)	
50–60 years	1313 (22.89)	402 (20.27)	911 (23.99)	
> 60 years	2674 (32.26)	1102 (36.54)	1572 (30.47)	
Race/ethnicity				< 0.0001
Non-Hispanic White	2821 (69.37)	955 (64.45)	1866 (71.44)	
Non-Hispanic Black	1441 (9.93)	564 (12.34)	877 (8.92)	
Mexican American	890 (7.22)	353 (9.26)	537 (6.37)	
Other race	1598 (13.47)	494 (13.95)	1104 (13.27)	
Educational attainment				< 0.0001
Grades 0–12	1564 (14.61)	832 (25.76)	732 (9.93)	
High school graduate/GED	1464 (22.13)	559 (24.07)	905 (21.32)	
Some college or above	3722 (63.26)	975 (50.17)	2747 (68.75)	
Frequency of recreational activity				< 0.0001
No	3656 (47.11)	1563 (61.62)	2093 (41.02)	
Moderate	1856 (30.65)	556 (25.94)	1300 (32.62)	
Vigorous	368 (6.12)	100 (5.33)	268 (6.46)	
Both	870 (16.12)	147 (7.11)	723 (19.90)	
PIR				< 0.0001
< 1.3	2029 (19.25)	994 (31.75)	1035 (14.01)	
≥ 1.3 < 3.5	2489 (34.21)	872 (36.85)	1617 (33.10)	
≥ 3.5	2232 (46.54)	500 (31.40)	1732 (52.89)	

Abbreviation: PIR, poverty–income ratio.
**p*-values were calculated by survey-weighted chi-square test.

among participants aged > 60 years, there were 1572 participants in the dental floss user group compared with 1102 participants in the dental floss non-user group. In terms of race, about half of the participants were non-Hispanic White; among them, 1866 reported using dental floss compared with 955 who did not. Participants with a higher level of education (2747) and PIR ≥ 3.5 (1732) were more likely to use dental floss. Regarding recreational activity levels, a total of 3656 participants engaged in less recreational activity, of which 2093 belonged to the dental floss user group and 1563 belonged to the dental floss non-user group. Statistical analysis revealed significant differences between dental floss users and non-users regarding participant demographics, including sex, age, race/ethnicity, educational attainment, PIR and frequency of recreational activity. Furthermore, it was found that dental floss users showed a higher probability of being female individuals of Non-Hispanic White ethnicity with higher levels of education ($p < 0.0001$).

3.2 | Correlation Between Serum PFAS Levels and the Use of Dental Floss

The study findings showed that dental floss users had lower serum concentrations of PFHSA, PFOSA, PFDA and MeFOSAA compared with non-users in the covariate-adjusted model. Conversely, the serum concentrations of PFOA were higher in dental floss users compared with non-users, showing a statistically significant difference between the two groups in the covariate-adjusted model ($p < 0.0001$). The overall burden of the six PFASs was lower in dental floss users compared with

TABLE 2 | Correlation between serum perfluoroalkyl and polyfluoroalkyl substance (PFAS) levels and dental floss use status among U.S. adults.

	Unadjusted mean (95% confidence interval)					Covariate-adjusted mean (95% confidence interval)				
		Dental floss					Dental floss			
Variable	**Total ($n=6750$)**	**No ($n=2366$)**	**Yes ($n=4384$)**	***p***	**Adjusted *p*-value***	**Total ($n=6750$)**	**No ($n=2366$)**	**Yes ($n=4384$)**	***p***	**Adjusted *p*-value***
PFOA	2.545 (2.391–2.698)	2.513 (2.355–2.672)	2.558 (2.392,2.723)	0.484	0.661	2.584 (2.558–2.610)	2.534 (2.500–2.567)	2.605 (2.578–2.632)	< 0.0001	< 0.0001
PFNA	1.015 (0.942–1.088)	1.005 (0.906–1.105)	1.019 (0.950–1.087)	0.701	0.701	1.031 (1.022–1.039)	1.02 8 (1.015–1.041)	1.032 (1.022–1.041)	0.636	0.636
PFHS	1.947 (1.841–2.052)	2.008 (1.854–2.161)	1.921 (1.798–2.043)	0.337	0.661	1.973 (1.950–1.996)	2.019 (1.986–2.053)	1.953 (1.928–1.979)	< 0.001	< 0.001
PFOS	7.628 (6.935–8.321)	8.143 (7.375–8.910)	7.412 (6.632–8.192)	0.066	0.231	7.900 (7.800–8.000)	8.442 (8.288–8.595)	7.673 (7.553–7.792)	< 0.0001	< 0.0001
PFDA	0.300 (0.283–0.316)	0.294 (0.265–0.322)	0.302 (0.285–0.319)	0.567	0.661	0.305 (0.300–0.309)	0.317 (0.309–0. 324)	0.300 (0.295–0.304)	< 0.0001	< 0.0001
MeFOSAA	0.220 (0.208–0.233)	0.241 (0.215–0.267)	0.212 (0.199–0.224)	0.039	0.231	0.232 (0.229–0.235)	0.241 (0.237–0.245)	0.228 (0.225–0.232)	< 0.0001	< 0.0001
Overall PFAS burden score	3.237 (3.181–3.294)	3.256 (3.196–3.316)	3.229 (3.165–3.293)	0.385	0.661	3.253 (3.240–3.266)	3.260 (3.241–3.279)	3.250 (3.234–3.265)	0.342	0.399

*Adjusted *p*-values for multiple comparisons were calculated using the false discovery rate method. The model was adjusted for sex, age, race/ethnicity, education attainment, frequency of recreational activities and PIR (poverty–income ratio). The overall PFAS burden score included all six targeted PFAS compounds. The unit of PFAS compounds is ng/mL.

non-users (Table 2). Overall, dental floss users recorded a lower level of overall burden compared with non-users. Furthermore, in each NHANES cycle, the serum concentrations of PFOA were higher in dental floss users compared with non-users. The overall burden of the six PFASs was generally lower among dental floss users compared to non-users, with the exception of the 2015–2016 cycle (Table S1).

3.3 | Sensitivity Analysis

To eliminate the influence of the frequency of recreational activities on dental floss use status, we conducted further analysis. After excluding recreational activities, we found that dental floss users showed significantly higher levels of serum PFOA compared to non-users, with the results being statistically significant ($p < 0.001$). Regarding the overall PFAS burden, however, the findings indicated that dental floss users had lower levels compared to non-users (Table S2).

We also constructed several models to investigate the impact of dental floss use frequency on the six PFASs and the overall PFAS burden. In all models (unadjusted model; adjusted model 1, which was controlled for sex, age, race/ethnicity, education and PIR; and adjusted model 2, which was controlled for sex, age, race/ethnicity, education, PIR and recreational activity), no statistically significant association was found between dental floss use frequency and the overall PFAS burden. For the levels of serum PFOA, we observed the same results in all three models (Table S3). To further investigate the impact of the frequency of dental floss use on the results, we categorized participants into three groups based on the frequency of dental floss use (0–1 days/week, 2–4 days/week and 5–7 days/week). Sensitivity analyses were conducted accordingly. The findings indicated that, among all participants, using dental floss 2–4 days/week was associated with MeFOSAA in the unadjusted model. However, no significant correlation was observed between the frequency of dental floss use and levels of PFOA or overall PFAS burden in either subgroup analyses or correlation models (Table S4).

3.4 | Distribution of Serum PFAS Concentrations in Dental Floss Users

The distribution of serum PFAS concentrations among dental floss users showed distinct patterns across different compounds, as shown in Figure 2. The density plot indicated a similar distribution of PFOA between dental floss users and non-users; however, the cumulative probability plot suggested slightly higher concentrations of PFOA among dental floss users. A similar trend was observed for PFNA, with dental floss users showing a slightly higher cumulative probability of elevated serum concentrations. Overlapping density distributions were found between dental floss users and non-users for PFHSA and PFOSA without any significant differences in cumulative probability. Regarding PFDA and MeFOSAA, the density plots showed a wider range in concentrations for dental floss users compared with non-users, while the cumulative distributions indicated higher serum levels in dental floss users for both compounds. We further conducted box plot and violin plot analyses, which further confirmed the distribution of the six PFASs (Figures S1 and S2).

4 | Discussion

PFASs show widespread exposure in the human living environment, with detrimental effects on human health due to their prolonged half-life and other associated properties. Because individuals can be exposed to PFASs in all aspects of their daily lives, assessing the risks associated with PFAS exposure is critical to protecting public health. A previous study has indicated that the use of dental floss containing PTFE may increase an individual's susceptibility to PFAS exposure (Boronow et al. 2019). In contrast with prior findings, our study observed that dental floss users showed both higher and lower serum PFAS levels depending on the specific compound. Specifically, the findings showed that the serum concentrations of PFOA were significantly higher in dental floss users than in non-users, and this difference was statistically significant. In contrast, dental floss users exhibited decreased serum concentrations of PFHSA, PFOSA, PFDA, MeFOSAA and overall PFAS burden compared with non-users. These results suggest a more nuanced relationship between dental floss use and PFAS exposure, where some compounds may be affected differently. In the sensitivity analysis, after excluding the influence of recreational activities, we found that the serum concentrations of PFOA were still significantly higher among dental floss users compared with non-users. This finding provided further evidence that the use of dental floss may lead to increased serum concentrations of PFOA. Other PFASs, as well as the overall PFAS burden, were influenced by recreational activities, leading to significant fluctuations. Nevertheless, the overall results still indicated a decreasing trend in serum concentrations of relevant PFASs and the overall PFAS burden among dental floss users.

The distribution of serum PFAS concentrations among dental floss users shows distinct patterns, as highlighted by the density plots, cumulative probability plots, box plots and violin plots. The results indicated a slight increase in the concentrations and cumulative levels of PFOA among dental floss users compared with non-users, which was consistent with our previous analysis. However, the concentrations and cumulative levels of other related PFASs varied between dental floss users and non-users. This suggests that while certain PFASs may not show significant differences in concentrations between dental floss users and non-users, their cumulative levels may vary. These findings emphasize the importance of distinguishing between different PFASs when assessing potential health risks.

PFASs have been linked to various diseases, including prostate hyperplasia (Wang et al. 2024), polycystic ovary syndrome (Li et al. 2024), diabetes (Gui et al. 2023; Kang and Kim 2024), cardiovascular diseases (Schlezinger and Gokce 2024) and thyroid cancer (van Gerwen et al. 2023). Given the potential health risks associated with PFASs, reducing their exposure is critical. However, our research suggests that, contrary to previous assumptions, the use of dental floss may not universally increase serum PFAS levels in the human body; instead, it appears to only affect serum levels of certain PFASs (such as PFOA). The use of dental floss may lead to an increase in human serum PFOA concentrations, implying potential adverse effects. However, dental floss users showed a decreasing trend in the serum concentrations of PFHSA, PFOSA, PFDA and MeFOSAA, as well as a lower overall PFAS burden compared with non-users.

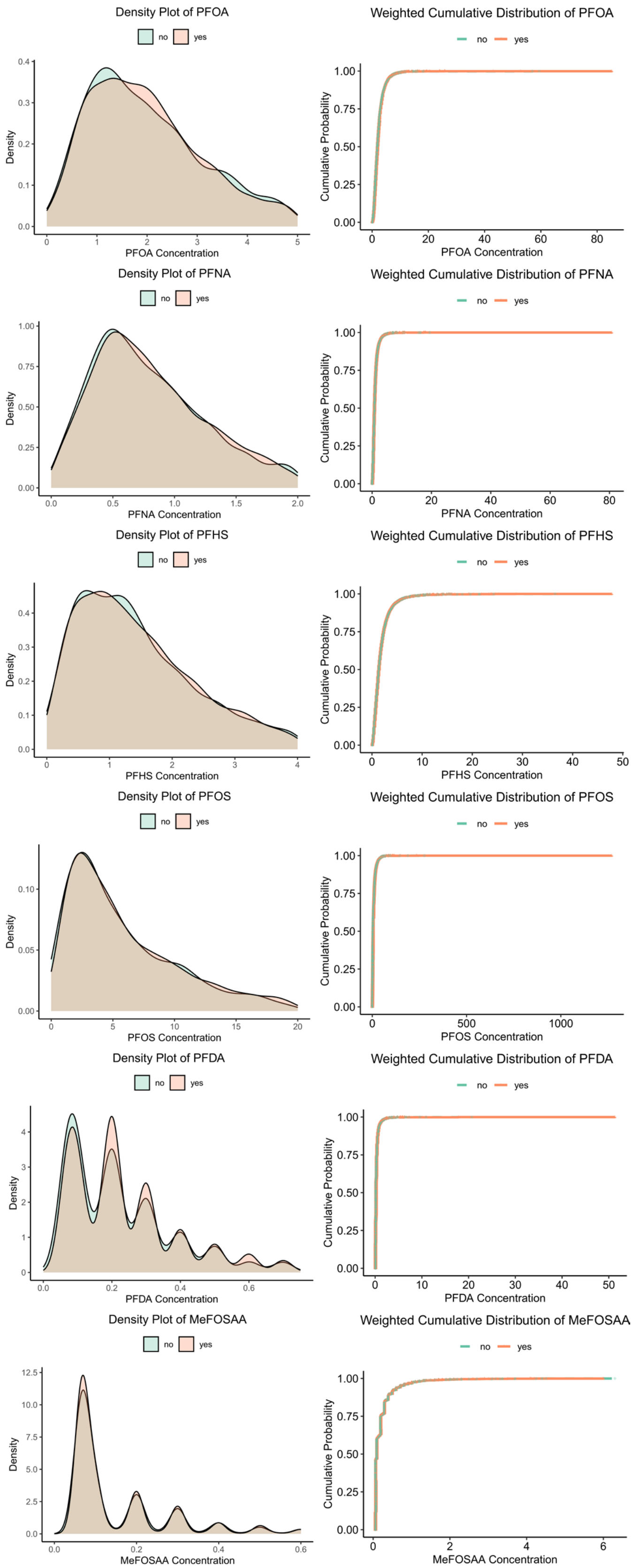

FIGURE 2 | Distribution of serum perfluoroalkyl and polyfluoroalkyl substance (PFAS) concentrations in dental floss users versus non-users among adults in the United States. 'Yes' denotes dental floss users and 'no' denotes non-users.

This decrease may be attributed to their good oral hygiene habits. These findings emphasize the need for a comprehensive understanding of the impact of dental floss on serum levels of PFASs from multiple perspectives. While dental floss is widely recommended for oral hygiene, its association with PFAS exposure may not be as straightforward as previously thought, calling for more nuanced safety evaluations.

PFASs are distributed in the atmosphere, water and soil, which serve as the main pathways for human exposure to these compounds (Jane et al. 2022). Humans may be exposed to PFAS through ingestion of contaminated water, food and dust. Additionally, previous studies have detected PFASs in non-stick cookware and food packaging such as fast-food wrappers (Jane et al. 2022; Skedung et al. 2024). People may indirectly ingest PFASs by consuming water or food that has come into contact with these materials. As mentioned above, while dental floss may contribute to exposure to PFASs, it is unlikely to be the primary driver of PFAS exposure for most individuals. Relevant studies have identified the existence of PFASs in dental floss products (Boronow et al. 2019; Skedung et al. 2024); however, few studies have further explored the potential exposure to PFASs associated with the use of these dental floss products. Many oral care products, including dental floss, contain related PFASs to improve product smoothness and user experience (Massarsky et al. 2024; Skedung et al. 2024). Therefore, understanding the potential sources of PFAS exposure can help individuals to mitigate the associated risks.

Owing to the limitations of the NHANES data, which do not specify brand usage, we are unable to provide precise estimates of PFAS exposure from specific dental floss brands in our current study. However, this limitation underscores the need for further research to isolate the effects of different brands and types of dental floss. The increase in serum PFOA concentrations found in our study among dental floss users may be attributed to specific brands of dental floss that contain PFASs. Considering the declining trend in serum concentrations of other PFASs among dental floss users, it is reasonable to infer that the effects of PFOA identified from a limited number of dental floss brands containing PFASs may be higher than expected, particularly given the overall low usage of PFASs in dental floss across the market. Dental floss containing PFASs might only represent a small fraction of the market, but exposure levels for these particular products can be significant for individuals who regularly use them. However, it is important to note that our study primarily serves as an indication for potential areas of future research rather than serving as a basis for immediate public health action. Future research should aim to distinguish between PFAS-containing and PFAS-free dental floss by correlating consumer reports and product test results with relevant serum PFAS levels. The potential for dental floss to cause PFAS exposure is a minor concern, and we must be cautious in interpreting the possible health effects, especially because only a small percentage of people are likely to exceed these thresholds.

The present study provides one of the first comprehensive analyses exploring the complex relationship between dental floss usage and specific PFASs in the general population. Our findings suggest that dental floss usage is associated with varying serum concentrations of several PFASs, and elevated serum concentrations of PFOA may indicate a potential risk, emphasizing the need for future research on product-specific PFAS exposures. Dental floss is an essential tool for daily oral hygiene. The components of dental floss should be carefully examined and used appropriately to reduce potential PFAS exposure. However, limitations exist in our study, such as the reliance on self-reported data from the NHANES database, which may underreport dental floss usage or fail to account for variations across different brands and materials. Future prospective studies are needed to verify these findings and explore potential strategies for mitigation.

5 | Conclusion

Our findings suggest that the use of dental floss may have a differential association with serum concentrations of specific PFASs. Among a large representative sample of U.S. adults, individuals reporting the use of dental floss had lower levels of serum PFASs overall. While serum concentrations of PFOA were found to be higher among dental floss users, indicating a potential adverse effect, other compounds such as PFHSA, PFOSA and PFDA were recorded at lower levels in dental floss users. Therefore, dental floss, as an important oral hygiene aid in daily life, requires further scrutiny to fully understand its role in PFAS exposure and to avoid any potential risks at present or in the future. Given these complex associations, dental floss manufacturers should carefully evaluate the materials used in their products and take targeted actions to reduce the presence of PFASs and related compounds, thereby minimizing any potential impact on users' health.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Ankley, G. T., P. Cureton, R. A. Hoke, et al. 2021. "Assessing the Ecological Risks of Per- and Polyfluoroalkyl Substances: Current State-of-the Science and a Proposed Path Forward." *Environmental Toxicology and Chemistry* 40, no. 3: 564–605. https://doi.org/10.1002/etc.4869.

Armstrong, L. E., and G. L. Guo. 2019. "Understanding Environmental Contaminants' Direct Effects on Non-Alcoholic Fatty Liver Disease Progression." *Current Environmental Health Reports* 6, no. 3: 95–104. https://doi.org/10.1007/s40572-019-00231-x.

Boone, J. S., C. Vigo, T. Boone, et al. 2019. "Per- and Polyfluoroalkyl Substances in Source and Treated Drinking Waters of the United States." *Science of the Total Environment* 653: 359–369. https://doi.org/10.1016/j.scitotenv.2018.10.245.

Boronow, K. E., J. G. Brody, L. A. Schaider, G. F. Peaslee, L. Havas, and B. A. Cohn. 2019. "Serum Concentrations of PFASs and Exposure-Related Behaviors in African American and Non-Hispanic White

Women." *Journal of Exposure Science & Environmental Epidemiology* 29, no. 2: 206–217. https://doi.org/10.1038/s41370-018-0109-y.

Boronow, K. E., B. Cohn, L. Havas, M. Plumb, and J. G. Brody. 2023. "The Effect of Individual or Study-Wide Report-Back on Knowledge, Concern, and Exposure-Reducing Behaviors Related to Endocrine-Disrupting Chemicals." *Environmental Health Perspectives* 131, no. 9: 97005. https://doi.org/10.1289/ehp12565.

Coperchini, F., A. Greco, L. Croce, et al. 2024. "Do PFCAs Drive the Establishment of Thyroid Cancer Microenvironment? Effects of C6O4, PFOA and PFHxA Exposure in Two Models of Human Thyroid Cells in Primary Culture." *Environment International* 187: 108717. https://doi.org/10.1016/j.envint.2024.108717.

Curtzwiler, G. W., P. Silva, A. Hall, A. Ivey, and K. Vorst. 2021. "Significance of Perfluoroalkyl Substances (PFAS) in Food Packaging." *Integrated Environmental Assessment and Management* 17, no. 1: 7–12. https://doi.org/10.1002/ieam.4346.

Ding, N., S. D. Harlow, J. F. Randolph Jr., R. Loch-Caruso, and S. K. Park. 2020. "Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) and Their Effects on the Ovary." *Human Reproduction Update* 26, no. 5: 724–752. https://doi.org/10.1093/humupd/dmaa018.

Evich, M. G., M. J. B. Davis, J. P. McCord, et al. 2022. "Per- and Polyfluoroalkyl Substances in the Environment." *Science* 375, no. 6580: eabg9065. https://doi.org/10.1126/science.abg9065.

Gluge, J., M. Scheringer, I. T. Cousins, et al. 2020. "An Overview of the Uses of Per- and Polyfluoroalkyl Substances (PFAS)." *Environmental Science. Processes & Impacts* 22, no. 12: 2345–2373. https://doi.org/10.1039/d0em00291g.

Gui, S. Y., J. C. Qiao, K. X. Xu, et al. 2023. "Association Between Per- and Polyfluoroalkyl Substances Exposure and Risk of Diabetes: A Systematic Review and Meta-Analysis." *Journal of Exposure Science & Environmental Epidemiology* 33, no. 1: 40–55. https://doi.org/10.1038/s41370-022-00464-3.

Hitz Lindenmüller, I., and J. T. Lambrecht. 2011. "Oral Care." *Current Problems in Dermatology* 40: 107–115. https://doi.org/10.1159/000321060.

Holder, C., E. A. Cohen Hubal, J. Luh, M. G. Lee, L. J. Melnyk, and K. Thomas. 2024. "Systematic Evidence Mapping of Potential Correlates of Exposure for Per- and Poly-Fluoroalkyl Substances (PFAS) Based on Measured Occurrence in Biomatrices and Surveys of Dietary Consumption and Product Use." *International Journal of Hygiene and Environmental Health* 259: 114384. https://doi.org/10.1016/j.ijheh.2024.114384.

Huang, Z., J. M. Broadbent, and J. J. E. Choi. 2023. "Comparison of Dental Flosses—An Investigation of Subjective Preference and Mechanical Properties." *Biomaterial Investigations in Dentistry* 10, no. 1: 2258919. https://doi.org/10.1080/26415275.2023.2258919.

Jane, L. E. L., M. Yamada, J. Ford, G. Owens, T. Prow, and A. Juhasz. 2022. "Health-Related Toxicity of Emerging Per- and Polyfluoroalkyl Substances: Comparison to Legacy PFOS and PFOA." *Environmental Research* 212, no. Pt C: 113431. https://doi.org/10.1016/j.envres.2022.113431.

Kang, H., and S. H. Kim. 2024. "Associations Between Serum Perfluoroalkyl and Polyfluoroalkyl Concentrations and Diabetes Mellitus in the Korean General Population: Insights From the Korean National Environmental Health Survey 2018-2020." *International Journal of Hygiene and Environmental Health* 259: 114385. https://doi.org/10.1016/j.ijheh.2024.114385.

Kim, D. H., J. H. Lee, and J. E. Oh. 2019. "Assessment of Individual-Based Perfluoroalkly Substances Exposure by Multiple Human Exposure Sources." *Journal of Hazardous Materials* 365: 26–33. https://doi.org/10.1016/j.jhazmat.2018.10.066.

Kuklenyik, Z., L. L. Needham, and A. M. Calafat. 2005. "Measurement of 18 Perfluorinated Organic Acids and Amides in Human Serum Using On-Line Solid-Phase Extraction." *Analytical Chemistry* 77, no. 18: 6085–6091. https://doi.org/10.1021/ac0506711.

Kvalem, H. E., U. C. Nygaard, K. C. Lødrup Carlsen, K. H. Carlsen, L. S. Haug, and B. Granum. 2020. "Perfluoroalkyl Substances, Airways Infections, Allergy and Asthma Related Health Outcomes - Implications of Gender, Exposure Period and Study Design." *Environment International* 134: 105259. https://doi.org/10.1016/j.envint.2019.105259.

Li, S., G. Li, Y. Lin, et al. 2024. "Association Between Perfluoroalkyl Substances in Follicular Fluid and Polycystic Ovary Syndrome in Infertile Women." *Toxics* 12, no. 2: 104. https://doi.org/10.3390/toxics12020104.

Liu, S. H., J. R. Kuiper, Y. Chen, L. Feuerstahler, J. Teresi, and J. P. Buckley. 2022. "Developing an Exposure Burden Score for Chemical Mixtures Using Item Response Theory, With Applications to PFAS Mixtures." *Environmental Health Perspectives* 130, no. 11: 117001. https://doi.org/10.1289/ehp10125.

Manojkumar, Y., S. Pilli, P. V. Rao, and R. D. Tyagi. 2023. "Sources, Occurrence and Toxic Effects of Emerging Per- and Polyfluoroalkyl Substances (PFAS)." *Neurotoxicology and Teratology* 97: 107174. https://doi.org/10.1016/j.ntt.2023.107174.

Marinho, V. C., J. P. Higgins, A. Sheiham, and S. Logan. 2003. "Fluoride Toothpastes for Preventing Dental Caries in Children and Adolescents." *Cochrane Database of Systematic Reviews* 2003, no. 1: Cd002278. https://doi.org/10.1002/14651858.Cd002278.

Massarsky, A., J. A. Parker, L. Gloekler, et al. 2024. "Assessing Potential Human Health and Ecological Implications of PFAS From Leave-In Dental Products." *Toxicology and Industrial Health* 40, no. 3: 91–103. https://doi.org/10.1177/07482337231224990.

National Academies of Sciences, Engineering, and Medicine. 2022. *Guidance on PFAS Exposure, Testing, and Clinical Follow-Up*. Washington, DC: National Academies Press.

Nian, M., Q. Q. Li, M. Bloom, et al. 2019. "Liver Function Biomarkers Disorder Is Associated With Exposure to Perfluoroalkyl Acids in Adults: Isomers of C8 Health Project in China." *Environmental Research* 172: 81–88. https://doi.org/10.1016/j.envres.2019.02.013.

Rickard, B. P., I. Rizvi, and S. E. Fenton. 2022. "Per- and Poly-Fluoroalkyl Substances (PFAS) and Female Reproductive Outcomes: PFAS Elimination, Endocrine-Mediated Effects, and Disease." *Toxicology* 465: 153031. https://doi.org/10.1016/j.tox.2021.153031.

Schlezinger, J. J., and N. Gokce. 2024. "Perfluoroalkyl/Polyfluoroalkyl Substances: Links to Cardiovascular Disease Risk." *Circulation Research* 134, no. 9: 1136–1159. https://doi.org/10.1161/circresaha.124.323697.

Skedung, L., E. Savvidou, S. Schellenberger, A. Reimann, I. T. Cousins, and J. P. Benskin. 2024. "Identification and Quantification of Fluorinated Polymers in Consumer Products by Combustion Ion Chromatography and Pyrolysis-Gas Chromatography-Mass Spectrometry." *Environmental Science. Processes & Impacts* 26, no. 1: 82–93. https://doi.org/10.1039/d3em00438d.

Stanifer, J. W., H. M. Stapleton, T. Souma, A. Wittmer, X. Zhao, and L. E. Boulware. 2018. "Perfluorinated Chemicals as Emerging Environmental Threats to Kidney Health: A Scoping Review." *Clinical Journal of the American Society of Nephrology* 13, no. 10: 1479–1492. https://doi.org/10.2215/cjn.04670418.

Stubleski, J., S. Salihovic, L. Lind, P. M. Lind, B. van Bavel, and A. Kärrman. 2016. "Changes in Serum Levels of Perfluoroalkyl Substances During a 10-Year Follow-Up Period in a Large Population-Based Cohort." *Environment International* 95: 86–92. https://doi.org/10.1016/j.envint.2016.08.002.

van Gerwen, M., E. Colicino, H. Guan, et al. 2023. "Per- and Polyfluoroalkyl Substances (PFAS) Exposure and Thyroid Cancer Risk." *eBioMedicine* 97: 104831. https://doi.org/10.1016/j.ebiom.2023.104831.

Wang, T., J. Yang, Y. Han, and Y. Wang. 2024. "Unveiling the Intricate Connection Between Per- and Polyfluoroalkyl Substances and Prostate Hyperplasia." *Science of the Total Environment* 932: 173085. https://doi.org/10.1016/j.scitotenv.2024.173085.

Wang, Z., A. M. Buser, I. T. Cousins, et al. 2021. "A New OECD Definition for Per- and Polyfluoroalkyl Substances." *Environmental Science & Technology* 55, no. 23: 15575–15578. https://doi.org/10.1021/acs.est.1c06896.

Zalla, L. C., J. Y. Yang, J. K. Edwards, and S. R. Cole. 2022. "Leveraging Auxiliary Data to Improve Precision in Inverse Probability-Weighted Analyses." *Annals of Epidemiology* 74: 75–83. https://doi.org/10.1016/j.annepidem.2022.07.011.

Zheng, G., S. M. Eick, and A. Salamova. 2023. "Elevated Levels of Ultrashort- and Short-Chain Perfluoroalkyl Acids in US Homes and People." *Environmental Science & Technology* 57, no. 42: 15782–15793. https://doi.org/10.1021/acs.est.2c06715.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.