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Article

Population demographic patterns in PFAS-neurological health research

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SUMMARY

The Institute of Medicine's Board on Health Sciences Policy emphasizes that accurately measuring race and ethnicity is crucial in health services research, as these factors influence the quality of care individuals receive, regardless of socioeconomic status. Perfluoroalkyl substances (PFAS), often called "forever chemicals", have been linked to various health issues, including neurological effects. While epidemiological studies have explored how PFAS impacts neurological health, participant demographic diversity remains underexamined. This study examined racial and ethnic representation in existing research on PFAS and neurological health outcomes. We hypothesized that, compared to the demographic distribution reported in the United States of America (U.S.) Census, minority groups would be underrepresented in these studies. We analyzed demographic reporting in neurological health studies identified through the PFAS-Tox Database, comparing racial and ethnic representation to U.S. Census data. Our analysis revealed significant disparities in racial and ethnic representation. White individuals were overrepresented by 12.8% ($p < 0.001$), while Black, Asian, and American Indian or Alaska Native individuals were underrepresented by 5.6% ($p < 0.001$), 6.1% ($p < 0.001$), and 1.3% ($p < 0.001$), respectively. Hispanic individuals were underrepresented by 8.2% ($p < 0.001$). Limitations, including geographic bias toward studies in Ohio and inconsistencies in race/ethnicity categorization, may have influenced these disparities. Future research should expand to more diverse regions, standardize demographic reporting, and adopt targeted recruitment strategies to improve inclusivity and support equitable public health interventions for PFAS exposure.

INTRODUCTION

There are many items found in everyday life which contain per- and polyfluoroalkyl substances (PFAS) (1). These chemicals are commonly utilized in many everyday products, like cookware with non-stick surfaces, fabrics that resist stains, and foams used in firefighting (1). Their primary function is to repel substances such as water and oil, which is why they are often chosen for these applications (2). The durability of PFAS is largely attributed to the strong carbon-fluorine bonds within their molecular structure, making them highly resistant to environmental degradation (3). This persistence has raised concerns about their long-term impact on both human health and the environment (4, 5). With the growing body of research on the health impacts of PFAS, understanding how race and ethnicity contribute to these effects is becoming more important (6, 7). Studies show that both location and race or ethnicity play major roles in determining PFAS exposure, resulting in different levels of impact among racial and ethnic groups (8). However, these differences may not stem from intrinsic biological differences but potentially result from systemic inequities, such as historical redlining, discriminatory zoning practices, and limited access to resources (9–11). Social factors such as race, ethnicity, income, and age can make some populations more susceptible to environmental hazards (9–11). These systemic inequities have resulted in higher exposure to environmental toxins, including PFAS, in low-income and racially diverse neighborhoods (8). For example, proximity to industrial facilities, reliance on contaminated water sources, and limited resources for mitigation disproportionately affect Black, Hispanic, and low-income populations (8–11).

Health services research needs to accurately measure race and ethnicity, according to the Institute of Medicine's Board on Health Sciences Policy (12, 13). Regardless of socioeconomic status, these factors can affect the quality of healthcare people receive (12, 13). These disparities highlight the need for careful consideration of racial and ethnic differences in health research to ensure equitable health outcomes (12, 13). Exposure to PFAS in the drinking water and the proximity of sources of PFAS to marginalized communities have not been adequately studied (6, 14). Sometimes exposure can occur through air and sea transport, reaching even populations remote from industrial PFAS sources (4). Once in the environment, PFAS can bioaccumulate in seafood chains, leading to human exposure through their diets (15). There is also growing evidence that higher PFAS levels may increase the risk of neurological development disorders, including developmental delays in children, cognitive impairments such as reduced attention and memory, and potential contributions to neurodegenerative diseases like Alzheimer's and Parkinson's disease (16, 17).

Epidemiological studies have examined the effects of PFAS on neurological health, but participant diversity in these studies remains unexamined (18). We studied the representation of race and ethnicity in existing research on PFAS and neurological health outcomes. We hypothesized that, compared to the demographic distribution reported in the United States of America (U.S.) Census, minority groups would be underrepresented in these studies. We analyzed demographic data from neurological health studies identified in the PFAS-Tox Database, comparing racial and ethnic

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representation to U.S. Census data to assess potential disparities in research participation. Our analysis revealed significant underrepresentation of minority groups in existing PFAS and neurological health studies compared to U.S. Census data, supporting our hypothesis. These findings underscore the need for more inclusive research practices in future PFAS-related health investigations to ensure broader demographic representation.

RESULTS

To test our hypothesis that minority groups are underrepresented in studies on PFAS and neurological health outcomes, we compared racial and ethnic representation in relevant research to U.S. Census data. We analyzed demographic information from 27 U.S.-based studies on PFAS and their impact on the nervous system and behavior identified through the PFAS-Tox Database, encompassing a total of 117,914 individuals with reported race or ethnicity (**Figure 1**). PFAS-Tox, a database available at Pfastoxdatabase.org, is an interactive tool that organizes scientific evidence on PFAS (19, 20). This tool allows users to search the literature using various criteria, including specific PFAS chemicals, health impacts, types of studies, effects in early life, monetary conflicts, and other relevant factors (19, 20). Of the 27 U.S. studies on the impact of PFAS on neurological health, 12 studies were conducted in Ohio, 8 nationwide, 2 in New York, 2 in California, and 1 each in New Jersey and Massachusetts (**Figure 2**).

The following is the racial composition of the individuals in the studies, excluding Hispanic/Latino individuals: 88.7% White alone (91,753 of 104,122; 95% CI 88.5% to 88.9%), 8.2% Black alone (8,470 of 104,122; 95% CI 8.0% to 8.4%), 0.3% Asian alone (361 of 104,122; 95% CI 0.3% to 0.4%), 0.01% American Indian or Alaska Native (12 of 104,122; 95% CI 0.00% to 0.02%), and 3.4% Unknown, which refer to individuals whose race was not reported or categorized under the listed groups, (3,526 of 104,122; 95% CI 2.7% to 3.1%) (**Figure 3**). We also analyzed "Hispanic or Latino" versus "Not Hispanic or Latino" independently of race and found that Hispanic individuals represented 11.3% of the participants (13,295 of 117,914; 95% CI: 11.1% to 11.5%) (**Figure 4**). None of the studies included individuals from the Native Hawaiian or Other Pacific Islander group. According to 2023 U.S. Census Bureau race estimates, the national population is composed of approximately 75.3% White alone, 13.7% Black alone, 6.4% Asian alone, 1.3% American Indian or Alaska Native alone, 0.3% Native Hawaiian or Other Pacific Islander alone, and 0.4% (21) (**Figure 3**). Additionally, the U.S. Census Bureau estimates that 19.5% of the population is of Hispanic or Latino ethnicity (21) (**Figure 4**). Our analysis of U.S.-based studies revealed significant disparities in racial and ethnic representation compared to U.S. Census data. White alone individuals were notably overrepresented, accounting for 12.8% more of the study population than their proportion in the general population. This overrepresentation was statistically significant (95% CI 12.6% to 13.0%; $p < 0.001$). In contrast, other racial groups were underrepresented. Black alone individuals were underrepresented by 5.6% (95% CI 5.4% to 5.7%; $p < 0.001$), Asian alone individuals were underrepresented by 6.1% (95% CI 6.0% to 6.1%; $p < 0.001$), American Indian or Alaska Native alone were underrepresented by 1.3% (95% CI 1.3% to 1.3%; $p < 0.001$), and Native Hawaiian or Other Pacific Islanders alone were underrepresented by 0.3% (95% CI 0.3% to 0.3%; $p < 0.001$). Unknown were slightly overrepresented by 0.3%, also statistically significant (95% CI 0.2% to 0.4%; $p < 0.001$) (**Figure 3**). Among ethnic groups, Hispanic or Latino individuals were underrepresented by 8.2% (95% CI: 8.0% to 8.4%; $p < 0.001$) (**Figure 4**). The proportion of racial and ethnic groups in the study sample were significantly different

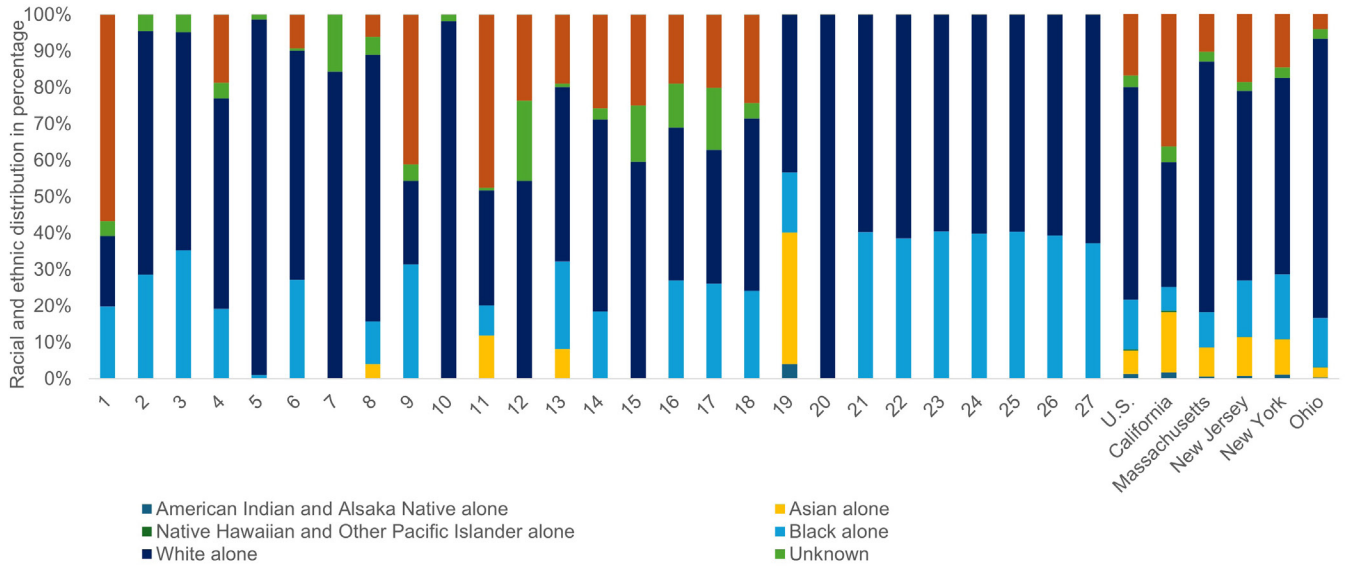

Figure 1: Breakdown of race/ethnicity categories in U.S. PFAS neurological health outcome studies. The figure displays the percentage of participants by race and ethnicity across 27 individual U.S. studies (bars 1–27), as well as aggregated data from the U.S. Census and the states where the studies were conducted. Data were extracted from the PFAS-Tox Database and reflect self-reported or study-reported race/ethnicity classifications. Race and ethnicity categories were reported as available in each study and standardized for comparison. None of the studies included participants identifying as Native Hawaiian or Other Pacific Islander.

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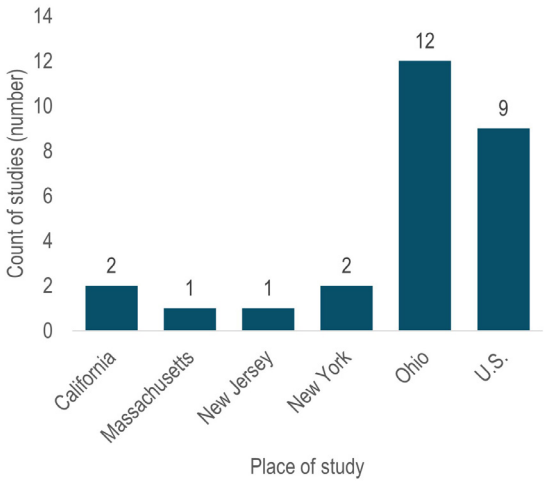

Figure 2: States where the U.S. PFAS neurological health outcome studies were conducted. The bars represent the count of studies in each state. Of the 27 U.S. studies on the effect of PFAS on neurological health, 12 studies were conducted in Ohio, 9 nationwide, 2 in New York, 2 in California, and 1 each in New Jersey and Massachusetts.

from their corresponding proportions in the U.S. Census population, supporting our hypothesis that minorities are underrepresented.

DISCUSSION

In humans, PFAS can produce adverse neurological outcomes (16). Our data for this study was taken from 27 studies in the U.S. on PFAS and neurological health outcomes taken from the PFAS-Tox Database. We hypothesized that minorities were underrepresented in the studies, as is often reported in health outcome research where systemic barriers, such as limited access to healthcare, socioeconomic disadvantages, and historical underrepresentation in research, contribute to disparities (6, 12, 22, 23). Analyzing the demographic differences between the U.S. Census and individuals surveyed in studies on PFAS and neurological health outcomes, we observed that white individuals were overrepresented, while Hispanic, Black, Asian, American Indian or Alaska Native, and Native Hawaiian or Other Pacific Islanders were underrepresented, which confirmed our hypothesis. Our results reveal an important deficiency in racial diversity within the existing research on PFAS and neurological health. The underrepresentation of minority groups in PFAS-related neurological health studies may lead to an incomplete understanding of how PFAS affect different populations, potentially exacerbating health disparities. Results predominantly based on white individuals may not accurately reflect the effects of PFAS on neurological health across all racial and ethnic groups, given potential differences in exposure patterns, genetic factors, and socioeconomic determinants of health (22, 23). Several factors may contribute to the observed disparities in representation, ranging from recruitment strategies that may not effectively reach minority communities, study locations that may not be accessible to diverse communities, socioeconomic barriers to participation (such as time constraints or lack of transportation), and potential distrust of medical research in some minority communities due to historical abuses.

There are several limitations in our study. Our study was limited to articles identified from the PFAS-Tox database and therefore may not represent all articles published on PFAS and neurological health outcomes in the U.S. Analyzed studies showed significant variation in how they defined and categorized race and ethnicity. A subset of the analyzed articles employed a limited racial categorization system, reporting only “non-Hispanic White” and “non-Hispanic Black

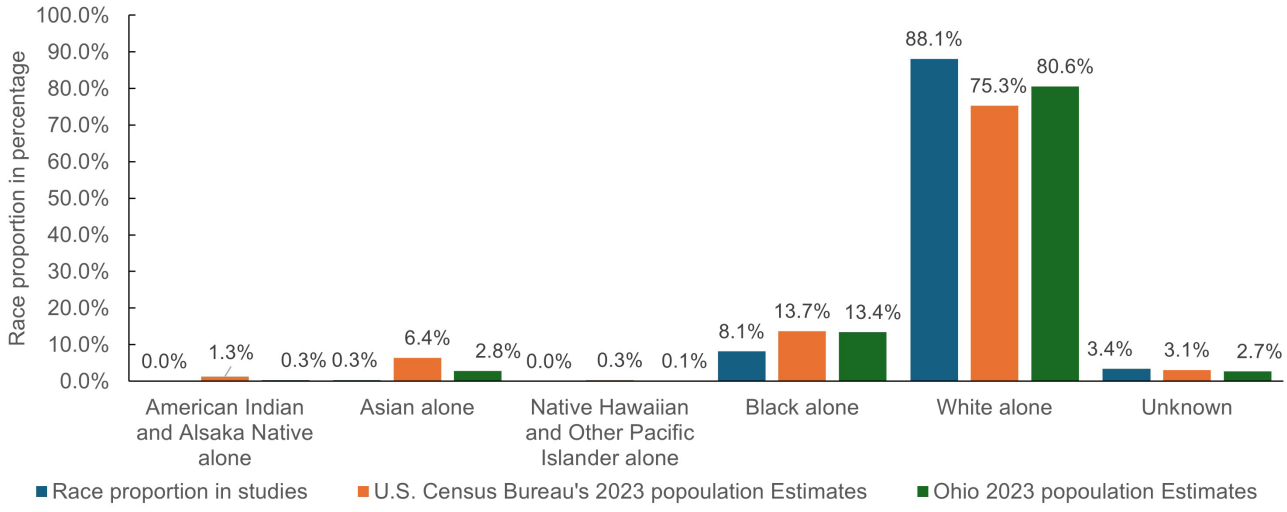

Figure 3: Comparison of combined proportion of race in PFAS neurological health outcome studies to U.S. Census. Blue bars represent the proportion of study participants in each racial category, orange bars represent the U.S. Census Bureau’s 2023 national estimates, and green bars represent the 2023 state-level estimates for Ohio, where the largest number of studies were conducted. The highest percentage of study individuals fell under “White alone” racial category and significantly different compared to expected racial demographic distribution based on data from the 2023 U.S. Census Bureau’s 2023 population estimates (p<0.001). All other races/ethnicities were severely underrepresented relative the 2023 U.S. Census Bureau’s 2023 population estimates (p<0.001). One-proportion z-tests compared the proportion of race of study individuals with the expected proportions from the U.S. Census data.

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and Others." This simplified classification scheme potentially underrepresents non-Black minority groups when compared to the more comprehensive U.S. Census race and ethnic groups. Consequently, this reporting approach may have led to an underestimation of the true diversity within the study populations, particularly for Hispanic, Asian, and other minority groups.

Sampling methods differed across the 27 studies likely contributed to the racial and ethnic representation disparities we observed in our analysis. For example, some studies used nationally representative sampling designs, such as the stratified, multistage approach employed by the National Health and Nutrition Examination Survey, which aims to reflect the broader U.S. population. In contrast, others used targeted recruitment strategies, such as enrolling pregnant women in the Health Outcomes and Measures of the Environment study or children at high risk for autism in the Markers of Autism Risk in Babies: Learning Early Signs study. While appropriate for answering specific research questions, these targeted approaches may limit generalizability and lead to underrepresentation of certain demographic groups. Furthermore, a significant limitation of our analysis is the disproportionate representation of studies conducted in a single state. Specifically, 12 out of the 27 studies (44.4%) in our sample were conducted in Ohio, a state with known high levels of PFAS contamination due to industrial activities such as those associated with the DuPont Washington Works plant in the Mid-Ohio Valley (**Figure 2**). While this focus provides valuable data on populations with high PFAS exposure, it introduces geographic bias, as the findings may not be generalizable to regions with lower or different types of exposure (e.g., water contamination vs. dietary sources). Ohio residents, particularly those near contaminated sites, may have unique demographic, environmental, and occupational characteristics influencing exposure and health outcomes. Additionally, since we tested each racial/ethnic category separately, there is a risk of finding significant differences by chance (Type I error) if many tests are performed.

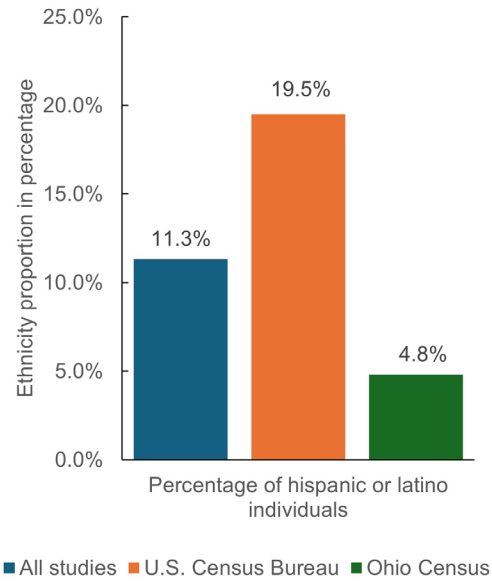

Figure 4: Comparison of the combined proportion of Hispanic or Latino ethnicity in studies about PFAS and neurological health outcomes to the U.S. Census. The blue bars represent the combined proportion of Hispanic or Latino ethnicity participants in all studies, and the orange bar represents the U.S. Census Bureau's 2023 Hispanic or Latino population estimates. For comparison, Hispanic or Latino population estimates are shown for the state of Ohio, where the largest number of studies were conducted (green bar). Hispanic or Latino ethnicity was underrepresented relative the 2023 U.S. Census Bureau's 2023 population estimates (p<0.001). One-proportion z-tests compared the proportion of study individuals with a given ethnicity with the expected proportion from the U.S. Census data.

The lack of diversity in PFAS and neurological health outcomes studies may have far-reaching consequences for public health policies and interventions related to PFAS exposure and neurological health. Policies based on research that underrepresents minority populations may fail to address the specific needs and risks of these communities, potentially widening health disparities (23). Additionally, our findings underscore the urgent need for more inclusive research practices to ensure that the health impacts of PFAS are thoroughly understood across all population groups (24). The studies reviewed investigated a range of neurological health outcomes, including cognitive impairment, attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorder (ASD), depression, and memory issues. The underrepresentation of minority groups in these studies raises concerns about whether the reported associations between PFAS exposure and these outcomes are fully generalizable. Given that PFAS exposure pathways (e.g., contaminated water, dietary sources) and neurological vulnerabilities may vary across populations, the lack of diversity in study populations limits our ability to understand the full scope of PFAS-related risks.

To address the disparities identified in this study, researchers should adopt culturally sensitive recruitment strategies that engage underrepresented communities. Collaborating with trusted community leaders and organizations can help build trust and awareness about PFAS research. Providing study materials in multiple languages, tailoring outreach efforts to align with cultural practices, and addressing literacy barriers can improve participation among diverse populations. Additionally, systemic barriers such as lack of transportation, childcare responsibilities, and financial constraints should be mitigated through practical support measures. For instance, offering transportation stipends, flexible participation schedules, and childcare services during research activities can make studies more accessible. Healthcare providers also play a critical role by identifying and referring patients from underrepresented groups for research participation. Training programs for providers that emphasize the environmental health risks of PFAS exposure, and the importance of inclusive research can further enhance engagement. By addressing these barriers and implementing targeted recruitment strategies, future research can ensure that study findings are representative and actionable, ultimately reducing health disparities and promoting environmental justice.

MATERIALS AND METHODS

Data Collection

Individual study papers were retrieved from PubMed and manually screened for study location and population

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characteristics. The data (study location, sample size, study year, race and ethnic distribution) was extracted and compiled in Microsoft Excel to perform statistical analysis. A summary of studies investigating PFAS exposure and neurological outcomes is provided in the Appendix (29 – 55). A total of 117,914 individuals were included across all 27 studies. Among these studies, 26% had a small sample size (< 200 individuals), 44% had a medium sample size (200 to 1,000 individuals), and 30% had a large sample size (> 1,000 individuals). Geographically, 44% were conducted in Ohio, 30% were national studies spanning multiple states, 7% were based in New York, 7% in California, and 3.7% in New Jersey and Massachusetts. Most studies employed longitudinal or cross-sectional designs, with data collection methods varying from convenience sampling in high-exposure areas to representative sampling via national databases like NHANES.

The U.S. federal government's racial and ethnic categorization system, which recognizes five racial groups: American Indians or Alaska Natives, Asians, Blacks, Native Hawaiians or Other Pacific Islanders, and Whites, was adopted (25, 26). The concept of ethnicity also groups individuals based on a shared cultural identity. In the U.S., ethnic groups are generally classified as either Hispanic or Latino, or non-Hispanic or Latino (25–27). The category "Unknown" was employed in the articles to categorize individuals whose specific race could not be identified. Based on these considerations, we established the following racial categories: White alone, Black alone, Asian alone, American Indian or Alaska Native alone, Native Hawaiian or Other Pacific Islander alone, and Unknown, as well as one ethnic category: Hispanic or Latino. To facilitate comparative analyses, relevant U.S. Census population characteristics were incorporated into the same dataset (21).

Statistical Techniques

First, the proportions of individuals of each racial and ethnic category in the dataset were computed with 95% confidence intervals for each proportion using the normal approximation method. To evaluate the differences in racial and ethnic distribution between the studies and the U.S. population, one-proportion z-tests were performed, which were appropriate for large samples because the normal approximations of the binomial distribution were valid, and these allowed for clear, category-level insights (28).

The 2023 population estimates from the U.S. Census Bureau were utilized as the baseline proportions for each racial and ethnic group. For each comparison, we calculated the z-statistic where $\hat{p}$ is the observed sample proportion, P_0 is the 2023 U.S. Census population proportion and n is the total sample size (**Equation 1**).

$$z = \frac{\hat{p} - P_0}{\sqrt{P_0(1-P_0)/n}}$$

We used two-tailed statistical tests to compare sample and census proportions (28). A significance threshold of $\alpha<0.05$ corresponding to a 95% confidence level was set for all tests. All statistical analyses were performed using Microsoft Excel.

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Appendix

Summary of studies investigating PFAS exposure and neurological health outcomes.

The figure highlights the study population, study year, and key demographic characteristics highlighting the inconsistent treatment of race/ethnicity in different studies.

Study	Study Name	Authors/ Publication Year	State/Population	Study Year(s)	Demographic Notes
1	PFAS and Depression	Berk et al. (2014) (29)	Nationwide	2005–2010	Race: Sampled from NHANES, represents U.S. diversity
2	PFAS and Autism	Braun et al. (2014) (30)	Ohio	2003–2006	Race: 67% White, 29% Black, 5% Other
3	PFAS and Child Obesity	Braun et al. (2016) (31)	Ohio	2003–2006	Race: 59.8% White, 35.2% Black, 4.9% Others
4	PFAS, Diabetes, and Microvascular Disease	Cardenas et al. (2019) (32)	Nationwide	1996–2014	Race: Diverse. 57.7% Caucasian, 19.2% African American, 18.7% Hispanic, 4.4% Others
5	Memory Impairment and PFAS	Gallo et al. (2013) (33)	Ohio	2005–2006	Race data predominantly White (97.6%), limiting generalizability
6	Water Contamination and PFAS	Graber et al. (2019) (34)	New Jersey	2009–2017	Race: 63% Non-Hispanic White, 27% Non-Hispanic Black, 9% Hispanic
7	PFC Exposure and Response Inhibition	Gump et al. (2011) (35)	New York	2008–2010	Race: 85% White, 15% Others

8	PFAS and Visual-Motor Skills	Harris et al. (2018) (36)	Massachusetts	1999–2010	Race: 73% White, 12% Black, 6% Hispanic, 4% Asian, 4% Others
9	PFAS and ADHD in Children	Hoffman et al. (2010) (37)	Nationwide	1999–2004	Race: Sampled from NHANES, represents U.S. diversity
10	PFAS and Stroke Risk	Hutcheson et al. (2020) (38)	West Virginia and Ohio	2005–2006	Race data predominantly White (98%), limiting generalizability.
11	PFAS and Autism Spectrum Disorder	Lyall et al. (2018) (39)	California	2000–2003	Race: 35% Non-Hispanic White, 9% Black, 41% Hispanic, 15% Asian, 1% Other
12	PFAS and High-Risk ASD Cohort	Oh et al. (2021) (40)	California	2009–2015	Race: Primarily non-Hispanic White 54%, 23% Hispanic and 21.9% Others
13	PFAS and Cognitive Decline	Park et al. (2021) (41)	Nationwide	2011–2014	Race: 40.7% Non-Hispanic White, 24% Non-Hispanic Black, 19% Hispanic, 8% Asian
14	PFC Exposure and Cognitive Limitation	Power et al. (2013) (42)	Nationwide	1999–2008	Race: Sampled from NHANES, represents U.S. diversity
15	Autism Spectrum Disorder and PFAS	Shin et al. (2020) (43)	California	2009–2017	Race: 53% Non-Hispanic White, 27% Hispanic, 19% Others
16	PFAS and Depression	Shiue et al. (2015) (44)	Nationwide	2011–2012	Race: Sampled from NHANES, represents

					U.S. diversity, 24% Others
17	PFAS and Memory	Shiue et al. (2015) (45)	Nationwide	2011–2013	Race: Sampled from NHANES, represents U.S. diversity
18	PFAS and Sleep Disturbance	Shiue et al. (2017) (46)	Nationwide	2005–2006	Race: Sampled from NHANES, represents U.S. diversity
19	Neurodevelopment and PFAS	Spratlen et al. (2020) (47)	New York	2001–2002	Race: Diverse urban population. 43% White, 17%, Black, 36% Asian
20	PFAS and ADHD Prevalence	Stein & Savitz (2011) (48)	Ohio	2005–2006	Race: 100% Non-Hispanic White
21	PFAS Exposure and Executive Function	Vuong et al. (2016) (49)	Ohio	2003–2006	Race: 62% Non-Hispanic White, 38% Non-Hispanic Black & Others
22	PFAS and Child Cognition	Vuong et al. (2018) (50)	Ohio	2003–2006	Race: 59.5% Non-Hispanic White, 40.5% Non-Hispanic Black
23	PFAS Exposure on Attention and Visual Spatial Abilities	Vuong et al. (2018) (51)	Ohio	2003–2006	Race: 59.6% Non-Hispanic White, 40.4% Non-Hispanic Black
24	PFAS Exposure and Cognitive Development	Vuong et al. (2019) (52)	Ohio	2003–2006	Race: 60% Non-Hispanic White, 40% Black
25	PFAS and Maternal Depression	Vuong et al. (2020) (53)	Ohio	2003–2010	Race: 60% Non-Hispanic White, 40% Black

26	Prenatal POP Exposure and Reading Skills	Vuong et al. (2020) (54)	Ohio	2003–2006	Race: 59.6% Non-Hispanic White, 40.4% Non-Hispanic Black
27	PFAS and Child Reading Skills	Zhang et al. (2018) (55)	Ohio	2003–2006	Race: 63% White, 37% Black