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Food Security and Blood Lead, Cadmium, and Mercury Among U.S. Children and Adolescents 1-19: National Health and Nutrition Examination Survey 2017 to 2023

A thesis submitted in partial satisfaction

of the requirements for the degree Master of Science

in Community Health Sciences

by

Isabella Campa

2026

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ABSTRACT OF THE THESIS

Food Security and Blood Lead, Cadmium, and Mercury Among U.S. Children and Adolescents 1-19: National Health and Nutrition Examination Survey 2017 to 2023

by

Isabella Campa

Master of Science in Community Health Sciences

University of California, Los Angeles, 2026

Professor Ondine S. von Ehrenstein, Chair

Exposure to toxic metals during childhood can adversely affect neurodevelopment and long-term health. Food insecurity may serve as an indicator of broader structural and environmental inequities that influence patterns of metal exposure. This study examined associations between household food security and blood concentrations of lead (Pb), cadmium (Cd), total mercury (THg), and methyl mercury (MeHg) among U.S. children and adolescents ages 1 to 19 using National Health and Nutrition Examination Survey (NHANES) 2017 to 2023 data. Survey weighted regression models estimated adjusted associations, and dietary factors were explored as potential co-factors or exposure pathways. Blood lead concentrations were modestly higher among children from households with lower food security, although associations were not statistically significant. Cadmium concentrations were similar across food

security categories. In contrast, THg and MeHg concentrations were 10-15% lower among children experiencing lower food security. Differences in fish consumption partially explained this pattern. These findings may suggest different environmental and dietary pathways linking food insecurity to metal exposures.

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The thesis of Isabella Campa is approved

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2026

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INTRODUCTION

Environmental Exposures in Children. Environmental exposures refer to contact with chemical, physical, or biological agents in air, water, food, and the surrounding environment that may affect human health. Exposure to environmental contaminants is widespread among U.S. children, with national biomonitoring studies consistently detecting toxic metals in blood and urine samples across the population. Although average levels of many contaminants have declined over recent decades due to public health and regulatory interventions, exposure remains a significant concern because some toxic metals can adversely affect health even at relatively low concentrations. Exposure burdens are also not distributed equally. Children living in low-income households, older housing, and communities disproportionately affected by environmental pollution often experience higher levels of exposure than their more advantaged peers (Landrigan et al., 2018).

Among environmental contaminants, toxic metals such as lead (Pb), cadmium (Cd), and mercury (Hg) are of particular concern because they persist in the environment and can accumulate in human tissues over time. Persistence refers to the ability of these metals to remain in soil, water, dust, and food for years or decades after their release, creating ongoing opportunities for exposure. Exposure can occur through ingestion of contaminated food or drinking water, inhalation of polluted air, or contact with contaminated dust and soil (Tchounwou et al., 2014). Lead exposure has been associated with reduced cognitive function, behavioral problems, and impaired neurodevelopment, and no safe blood lead level in children has been identified (Lanphear et al., 2005). Cadmium exposure has been linked to kidney dysfunction and impaired bone health. While mercury, particularly methyl mercury, is a well-

established neurotoxicant that can adversely affect learning, memory, and cognitive development.

Children are especially vulnerable to these exposures due to both physiological and behavioral factors. Compared with adults, children absorb certain contaminants more efficiently, have immature detoxification systems, and undergo rapid neurological and physical development, increasing susceptibility to environmental hazards (Landrigan et al., 2018). In addition, behaviors such as hand-to-mouth activity and frequent contact with floors, soil, and household surfaces can increase exposure to contaminants present in dust, soil, food, and water. (Karagas et al., 2012).

The health impacts of these metals extend beyond childhood. Early life exposure can have long lasting consequences that persist into adulthood, affecting cognitive development and overall health trajectories (Grandjean & Landrigan, 2014). These long-term effects make it critical to understand patterns of exposure during childhood, and it is critical for identifying at risk populations and informing public health interventions. While overall exposure levels have declined in the United States, these declines have not been uniform, and disparities remain across socioeconomic and demographic groups.

For example, analyses of nationally representative NHANES data have shown that children living below the federal poverty line continue to experience higher blood lead concentrations than children from higher income households despite substantial national declines in exposure (Egan et al., 2021). Racial and ethnic disparities also persist. In NHANES, non-Hispanic Black children often exhibit higher blood lead concentrations than non-Hispanic White children, while non-Hispanic Asian populations frequently have substantially higher mercury concentrations, largely reflecting differences in environmental conditions, housing quality,

dietary patterns, and broader social and structural factors rather than biological differences (Song & von Ehrenstein, 2025). These findings suggest that environmental exposures remain socially patterned even when overall exposure levels decline at the population level.

Social Determinants of Environmental Exposure. Environmental exposures do not occur randomly; they are often shaped by social and structural factors. Among these factors, household food security has emerged as an important but understudied determinant of environmental exposure. Food insecurity, defined as limited or uncertain access to adequate food due to financial constraints, affects millions of households in the United States and is strongly linked to broader patterns of socioeconomic disadvantage (Cook et al., 2013). Although food insecurity is strongly associated with poverty, the two concepts are not interchangeable. Poverty is typically measured using household income relative to a federal threshold, whereas food insecurity captures the lived experience of economic hardship through limitations in food access and food purchasing power. Households with similar incomes may differ substantially in food security because of variation in housing costs, medical expenses, debt obligations, family composition, geographic access to food retailers, and other competing financial demands. Consequently, food insecurity may capture dimensions of material hardship that are not fully reflected by traditional income-based measures alone (Song & von Ehrenstein, 2025).

Food insecurity is typically studied in relation to nutrition and health outcomes, including diet quality, obesity, and chronic disease. Most environmental health studies have relied on traditional socioeconomic indicators such as income, poverty status, or educational attainment when examining disparities in environmental exposures. While these measures are important, they do not directly capture how economic constraints shape dietary choices, food access, or other material conditions that may influence environmental exposures. Food insecurity may

therefore provide additional insight into the mechanisms through which socioeconomic disadvantage becomes translated into environmental health risks. Households experiencing food insecurity often face multiple constraints, including limited financial resources, reduced access to high quality foods, and residence in neighborhoods with fewer resources and greater environmental risks. These conditions can shape both dietary and environmental pathways of exposure.

One pathway linking food insecurity to metal exposure is through diet. For instance, consumption of fish and shellfish is a major source of methyl mercury exposure, but these foods can be expensive and less accessible to lower income households (Groth, 2014). As a result, children in food insecure households may have lower mercury exposure due to reduced seafood intake, but this may also reflect broader differences in dietary quality. At the same time, lower cost foods may be more likely to be processed or sourced in ways that influence exposure to other contaminants, although these relationships are complex.

Another pathway involves the broader material and environmental conditions that frequently accompany food insecurity. Food insecurity often co-occurs with other forms of hardship, including housing instability, residence in older housing stock, and neighborhoods with fewer resources and greater environmental burdens. These conditions may increase opportunities for exposure to lead based paint, contaminated dust, aging water infrastructure, and other environmental hazards (Jacobs et al., 2009). These households may also be in areas with higher levels of environmental pollution or limited access to safe recreational spaces. In this way, food insecurity can serve as an indicator of broader structural disadvantages that influence multiple exposure pathways at the same time.

It's also important to consider how food insecurity intersects with other social determinants, including race/ethnicity. In the United States, food insecurity is disproportionately experienced by non-Hispanic Black and Hispanic households, this reflects longstanding structural inequities (Cook et al., 2013). These disparities reflect broader structural inequities that shape access to economic opportunities, housing quality, neighborhood conditions, educational resources, and food access. Such factors influence both household food security and opportunities for environmental exposures. These structural factors contribute to disparities in environmental exposures, making it important to examine how food insecurity and race/ethnicity together can shape risk patterns.

Taken together, these considerations suggest that food insecurity may capture a combination of dietary, environmental, and socioeconomic factors that may influence or be associated with exposure to toxic metals. Despite this, relatively few studies have examined food insecurity as a determinant or co-factor of exposure, particularly in children and adolescents. Understanding these relationships is critical for identifying populations at higher risk.

Food Insecurity Beyond Poverty. Although poverty and food insecurity are closely related, food insecurity may provide information that extends beyond household income alone. Income based measures indicate available financial resources but do not necessarily capture how those resources translate into daily living conditions. Two households with similar incomes may experience different levels of food security because of differences in household expenses, food prices, family size, access to transportation, or availability of community resources.

Food insecurity may therefore represent a mechanism through which socioeconomic disadvantage influences environmental exposures. Dietary constraints associated with food insecurity may alter consumption of foods linked to contaminant exposure, particularly fish and

shellfish, which are major sources of mercury exposure. At the same time, food insecurity frequently co-occurs with other forms of material hardship, including poorer housing conditions and neighborhood environments that may increase opportunities for exposure to contaminants such as lead. Examining food insecurity separately from income may therefore provide additional insight into how social and material conditions shape environmental exposures among children and adolescents.

What's Known. A substantial amount of research has documented that exposure to toxic metals is not evenly distributed across the U.S. population and is closely tied to socioeconomic conditions. Lead exposure, especially, has long been associated with structural disadvantage. Although average blood levels in children have declined drastically over the past several decades, disparities remain by income, housing conditions, and race/ethnicity (Hauptman et al., 2023). For instance, children living in lower-income households consistently exhibit higher blood lead concentrations than children from higher-income households. Racial and ethnic disparities have also been documented, with higher lead concentrations often observed among non-Hispanic Black children relative to non-Hispanic White children (Egan et al., 2021). These differences are thought to reflect unequal housing conditions, aging infrastructure, environmental contamination, and other structural factors that influence exposure opportunities. Children in lower income households are more likely to reside in older housing with lead-based paint, aged plumbing systems, and environmental contamination, all of which contribute to ongoing exposure risks. Analyses of NHANES data have shown that children from families below the poverty line continue to have higher blood lead concentrations compared to children from higher-income households, even at relatively low overall exposure levels (Egan et al., 2021). These differences are thought to reflect greater residence in older housing, aging plumbing

systems, environmental contamination, and other exposure related conditions associated with socioeconomic disadvantage.

Mercury exposure follows a different pattern, with diet, particularly fish and shellfish consumption, being the primary source of exposure in the general population. Methyl mercury, the organic form of mercury, bioaccumulates in aquatic food chains and is primarily consumed through seafood. Studies using NHANES data have consistently shown that individuals with higher fish consumption have significantly higher blood mercury concentrations (Cusack et al., 2017). Unlike lead, mercury exposure is often higher among individuals with greater socioeconomic resources, reflecting differences in dietary patterns, including access to and consumption of seafood. This creates a distinct exposure profile in which higher socioeconomic status may be associated with higher mercury levels but through a pathway that's also linked to nutritional benefits.

Evidence for cadmium exposure is less consistent. Cadmium is primarily acquired through long term dietary intake and tobacco smoke exposure. It accumulates in the body over time (Satarug et al., 2010). Some studies have found higher cadmium levels among individuals with lower socioeconomic status, potentially due to higher rates of smoking and environmental exposures. While others have reported weaker or inconsistent associations (Tellez-Plaza et al., 2012). In children, blood cadmium levels tend to be overall and variation across socioeconomic groups is often modest. As a result, the relationship between cadmium exposure and social determinants such as income, poverty, educational attainment, race/ethnicity, and housing conditions.

Taken together, existing research suggests that different metals are shaped by distinct exposure pathways. Lead exposure is closely tied to environmental conditions associated with

socioeconomic disadvantage, mercury exposure is strongly influenced by diet, and cadmium reflects longer term cumulative exposures with mixed socioeconomic patterning. However, most studies have examined these metals separately, and fewer have considered how multiple exposure may be patterned by broader social conditions.

What's Missing. Despite extensive research on environmental metals and health, relatively little work has been examined on household food security as a determinant of metal exposure, particularly among children and adolescents. Food insecurity is typically studied in relation to nutrition and chronic disease outcomes, but it also may capture broader material and environmental conditions that influence exposure to contaminants. Since food insecurity reflects both constrained access to food and underlying socioeconomic disadvantage, it may serve as a useful indicator of multiple exposure pathways, including diet, housing, and environmental context.

The potential value of food insecurity as an exposure determinant lies in its ability to capture multiple pathways simultaneously. First, food insecurity may influence dietary choices and food purchasing behaviors. Certain foods associated with contaminant exposure, particularly fish and shellfish, may be consumed differently across food security groups because of differences in affordability and accessibility. This pathway may be especially relevant for mercury exposure, which is strongly influenced by seafood consumption. Second, food insecurity may reflect broader material conditions that influence environmental exposures. Households experiencing food insecurity are more likely to face other forms of hardship related to housing quality, neighborhood environments, and access to resources. These conditions may increase opportunities for exposure to contaminants such as lead through aging infrastructure, deteriorating housing, and environmental pollution.

Food insecurity may also capture aspects of lived material hardship that are not fully reflected by traditional measures of socioeconomic status. By examining food insecurity, it may provide additional insight into exposure related conditions beyond what can be learned from income based measures alone.

More prior studies examining metal exposure have focused on single metals or specific exposure pathways, rather than considering multiple metals simultaneously. This is an important limitation, as different metals have distinct sources and may be influenced by different aspects of the social environment. For example, while lead exposure may reflect housing and environmental conditions, mercury exposure is more closely tied to diet. Examining these metals together within the same population allows for a more comprehensive understanding of how social factors shape exposure patterns.

Relatively few studies have used nationally representative data to examine these relationships in children. NHANES provides a unique opportunity to assess multiple biomarkers of exposure alongside detailed information on diet, socioeconomic status, and household conditions. However, studies specifically linking food security to biomarker-based measures of metal exposure remain limited. Existing NHANES based research has examined associations between socioeconomic status and metals, as well as dietary predictors of mercury, but has not consistently integrated food security as a primary exposure of interest (Cusack et al., 2017; Tellez-Plaza et al., 2012).

Addressing these gaps requires an approach that considers multiple metals. Addressing these gaps also requires incorporating nationally representative data and examining food security as a structural determinant of exposure. By doing this it becomes possible to better understand

how social and environmental factors interact to shape exposure patterns in children and adolescents.

Study Purpose and Objectives. The purpose of this study was to examine how household food security is associated with exposure to toxic metals among U.S. children and adolescents. While prior research has documented socioeconomic and racial disparities in environmental exposures, fewer studies have considered food security as a central determinant that may capture or may be an indicator for both economic constraints and broader environmental context. Unlike traditional socioeconomic indicators such as income or poverty status, food security may simultaneously reflect dietary constraints, food access, material hardship, and environmental conditions that influence exposure opportunities. Examining food security therefore provides an opportunity to determine whether patterns of toxic metal exposure differ beyond what can be explained by income alone. Using nationally representative NHANES data, this study focused on three commonly studied metals, lead (Pb), cadmium (Cd), and mercury (Hg), each which reflected different exposure pathways. By analyzing these metals together, this study aimed to provide a more integrated understanding of how social conditions shape exposure patterns in childhood.

Another objective was to evaluate whether these associations differed across racial and ethnic groups. Previous research has documented racial and ethnic disparities in environmental exposures. Higher blood lead concentrations have frequently been observed among non-Hispanic Black children, while substantially higher mercury concentrations have been reported among non-Hispanic Asian populations. These differences are thought to reflect variation in housing conditions, environmental burdens, dietary practices, and broader structural inequalities rather than biological differences (Jacobs et al., 2009). Examining whether associations between food

security and metal exposure differ across racial and ethnic groups may therefore provide additional insight into the social patterning of environmental exposures.

The third study objective was to explore dietary pathways, specifically for mercury. Because methyl mercury exposure is strongly associated with fish and shellfish consumption, differences in diet associated with food insecurity may play an important role in shaping exposure patterns (Cusack et al., 2017). Incorporating dietary variables into the analysis allowed for evaluating whether observed differences in mercury levels were consistent with differences in seafood intake.

Research Questions. Based on these objectives this study was guided by these research questions:

1. Is household food security associated with blood concentrations of lead, cadmium, total mercury, and methyl mercury among U.S. children and adolescents?
2. Do associations between household food security and blood metal concentrations differ across racial and ethnic groups?
3. To what extent do dietary factors, particularly fish and shellfish consumption contribute to differences in mercury exposures across food security categories?

Hypotheses. The analysis was informed by several hypotheses. First, it was hypothesized that lower food security would be associated with higher blood lead concentrations, reflecting increased exposure to environmental risks associated with socioeconomic disadvantage. Second, it was hypothesized that lower food security would be associated with lower mercury concentrations, due to reduced consumption of fish and shellfish. No strong hypothesis was specified for cadmium due to mixed findings in prior research and the role of long-term

cumulative exposure (Satarug et al., 2010). It was hypothesized that adjusting for dietary variables would reduce associations between food security and mercury, consistent with dietary intake acting as a partial mediator.

LITERATURE REVIEW

Metal Exposures in Children. Exposure to toxic metals remains an important concern within child and adolescent health. Although population level exposures in the United States have declined over time, metals like lead (Pb), cadmium (Cd), and mercury (Hg) continue to be detected in children and are associated with a range of adverse health outcomes. These metals differ in terms of their sources and health effects, but they share several key characteristics. They can interfere with critical development, accumulate in the body, and are persistent in the environment (Landrigan et al., 2018).

Lead is one of the most heavily studied environmental toxicants in children and its effects on neurodevelopment are well established. There's no known safe level of lead exposure, and even low concentrations have been associated with measurable deficits in cognitive function. Previous studies have found that blood lead levels well below 10 ug/dL were associated with significant declines in IQ, with steeper effects seen at lower levels of exposure (Lanphear et al., 2005). More recent studies have supported these findings, demonstrating associations between early life lead exposure and impairments in attention (Vorvolakos et al., 2016).

The way lead causes harm is complicated, but it mainly affects how the brain develops, especially in children. Lead can cross the blood brain barrier and interfere with neurotransmitter release, which is essential for normal neurological development (Bellinger, 2013). Since these processes are most active during early childhood, exposure during this period can result in long term deficits that persist into adolescence and adulthood. Despite substantial declines in average

blood lead levels in the U.S. following regulatory actions like the removal of lead from gasoline and paint, exposure remains unevenly distributed. NHANES data indicate that while most children now have blood lead levels below 1 ug/dL, higher levels continue to be observed among children living in lower income households (Ruckart, 2021). These disparities highlight the continued relevance of lead both as a social and environmental health concern.

Cadmium is different from lead in both its exposure pathways and its biological behavior. While lead exposure often reflects current environmental conditions, cadmium exposure is typically chronic and cumulative. Cadmium is absorbed through diet, particularly through grains, leafy vegetables, and certain root plants, as well as through the inhalation of tobacco smoke. Once it is absorbed, cadmium accumulates in the body, especially in the liver and kidneys, with a biological half-life that can exceed 10 to 30 years (Satarug et al., 2010). Due to this long half-life, blood cadmium levels reflect both past and recent exposures. This makes it more difficult to link exposure to specific time periods or conditions. In children, cadmium concentrations are generally low compared to adults, but early life exposure may still have important implications. Chronic cadmium exposure has been associated with kidney dysfunction, bone demineralization, and potential effects on growth and development (Tellez-Plaza et al., 2012; Satarug et al., 2010). There's also emerging evidence that suggests that cadmium may affect metabolic processes and endocrine function, but these findings are less consistent than for lead. In population-based studies, patterns of cadmium exposure are less clearly defined than for lead. Some research has found that higher cadmium levels among individuals with lower socioeconomic status, often attributed to higher rates of smoking and environmental exposures, while other studies have reported weaker or inconsistent associations (Adams & Newcomb, 2013). In NHANES analyses, differences in blood cadmium across demographic groups tend to be modest, particularly among

children. This reflects the relatively low levels of exposure and the cumulative status of cadmium burden.

Mercury exposure, specifically in the form of methyl mercury (MeHg), is a distinct exposure compared to lead and cadmium. Methyl mercury is a potent neurotoxin that's primarily acquired through the consumption of fish and shellfish. In aquatic environments, inorganic mercury is converted by microorganisms into methyl mercury, it then bioaccumulates up to the food chain, resulting in higher concentrations in predatory fish (Karagas et al., 2012). In humans methyl mercury crosses both the blood brain barrier and the placenta, which makes it specifically concerning for developing fetuses and young children. Exposure during critical periods of brain development has been associated with deficits in attention, cognitive function, motor skills, and language development (Grandjean & Landrigan, 2014). These effects have been observed even at relatively low levels of exposure, which highlights the sensitivity of the developing nervous system of children. At the same time, mercury exposure through fish is a complex topic in public health. Fish are a major source of beneficial nutrients such as omega-3 fatty acids, that are important for brain development. As a result, dietary recommendations often balance the benefits of fish consumption with the risks of mercury exposure (Oken et al., 2012). The dual role of fish as both a source of nutrients and a pathway for exposure makes mercury distinct from other metals and demonstrates the importance of considering diet when interpreting mercury exposure patterns. In NHANES, both total mercury and methyl mercury are commonly analyzed because total mercury reflects overall mercury exposure, whereas methyl mercury specifically captures the neurotoxic organic form primarily derived from fish consumption.

NHANES data has consistently shown that blood mercury levels vary widely based on dietary habits, with higher concentrations observed among individuals who consume fish more

frequently (Cusack et al., 2017). As opposed to lead, mercury exposure is often higher among individuals with greater socioeconomic status and resources, reflecting differences in diet rather than environmental contamination. This nuance is important for understanding how different social and behavioral factors shape exposure to mercury and specific metals.

Taken together, lead, cadmium, and mercury represent three distinct but overlapping exposures in environments that impact children. Lead is closely linked to neurodevelopmental and environmental conditions such as housing and infrastructure. Cadmium reflects long term cumulative exposure through smoking-related and dietary pathways, with less clearly defined patterns in children. Mercury, particularly methyl mercury, is strongly tied to diet and combines various risks and benefits through fish consumption. Understanding these differences is important for interpreting patterns of exposure and for identifying the social and environmental factors that contribute to disparities in children's health.

Sources of Exposures. Environmental sources remain a primary pathway for lead exposure in children. Although the use of lead in gasoline, paint, and consumer products has been restricted in the U.S., contamination persists, particularly in older housing and urban environments. Lead based paint in homes built before 1978 continues to be a major source of exposure, especially when paint deteriorates and produces contaminated dust that can be ingested or inhaled (Jacobs et al., 2009). Children are especially vulnerable to this pathway due to frequent hand to mouth behaviors and time spent in indoor environments. In addition to housing, environmental pollution contributes to metal exposure through air, water, and soil. Lead contaminated soil, often found near roadways or industrial sites, can be tracked indoors and contribute to household dust exposure (Zartarian et al., 2017). Drinking water can also be a source of lead exposure when it passes through aging infrastructure, as seen in cases such as the

Flint water crisis (Hanna-Attisha et al., 2016). These exposures are not evenly distributed and are more common in communities with older infrastructure and fewer resources for maintenance and remediation.

Cadmium exposure also has environmental components, though these are often less visible. Industrial emissions, waste disposal, and agricultural practices can introduce cadmium into soil and water systems. Where it can persist and enter the food chain (Satarug et al., 2010). Inhalation of tobacco smoke, including secondhand smoke, is another important environmental source of cadmium, especially for children living in households where smoking occurs (Adams & Newcomb, 2013). Since cadmium accumulates over time, both current and past environmental conditions contribute to overall exposure.

Mercury exposure through environmental sources is less direct in most populations but environmental contamination still plays a role through the aquatic food chain. Industrial emissions release inorganic mercury into the atmosphere, which is deposited into water bodies and converted by microorganisms into methyl mercury. This then bioaccumulates in fish and shellfish, creating a link between environmental pollution and human exposure through diet (Karagas et al., 2012). While mercury exposure is often discussed in dietary terms, it can reflect broader environmental contamination processes.

Diet is a key pathway for exposure to several metals, particularly mercury and cadmium. For mercury, the primary source is fish and shellfish consumption. Methyl mercury accumulates in aquatic food chains, leading to higher concentrations in larger, predatory fish like tuna, shark, and swordfish. As a result, individuals who consume fish more frequently tend to have higher blood mercury levels, this is also a pattern that has been consistently observed in NHANES data (Cusack et al., 2017).

Although simultaneously, fish consumption is associated with important nutritional benefits, including intake of omega-3 fatty acids and high-quality protein, it increases risk for mercury exposure. This created a complex exposure scenario in which foods that contribute to positive health outcomes may also serve as a source of contaminant exposure (Oken et al., 2012). Differences in dietary patterns, including the types of frequency of fish consumed, can therefore have a significant impact on mercury exposure. Cadmium exposure through diet occurs primarily through plant-based foods, including leafy vegetables, grains, and root vegetables like rice and potatoes. These foods can accumulate cadmium from contaminated soil and water, specifically in areas with agricultural or industrial contamination (Satarug et al., 2010). Unlike mercury, dietary cadmium exposure tends to be more spread as these foods are commonly consumed across populations. As a result, differences in cadmium exposure through diet may be less pronounced, especially in children. Lead exposure through diet is generally less significant than environmental pathways but can still occur through contaminated food or water. Lead can enter the food supply through soil contamination, food processing, or packing materials, although regulations have reduced these sources over time (Ruckart, 2021). In children, ingestion of contaminated dust or soil is typically a more important source of exposure than diet.

A key aspect of metal exposure is that it's socially patterned, meaning that exposure levels differ systematically across socioeconomic groups. While socioeconomic status has traditionally been used to study environmental exposure disparities, food insecurity may capture additional dimensions of material hardship that are not fully reflected by income measures alone. Income provides information about financial resources, whereas food insecurity reflects how those resources translate into daily living conditions, dietary choices, and access to necessities. As a result, food insecurity may offer additional insight into the mechanisms through which

social disadvantage influences environmental exposures. These differences arise from a combination of environmental, behavioral, and structural factors. For lead, higher exposure is consistently associated with lower socioeconomic status, reflecting differences in housing quality, neighborhood conditions, and environmental risks (Benfer, 2024). Children in lower income households are more likely to live in older housing with lead hazards and in areas with greater environmental contamination. Mercury exposure oftentimes shows the opposite pattern, with higher levels observed among individuals with greater socioeconomic resources. This is largely due to differences in diet, as higher income households are more likely to consume fish and seafood regularly (Kr et al., 2004). As a result, mercury exposure can reflect dietary patterns associated with both higher socioeconomic status and cultural food preferences.

Cadmium exposure shows less consistent socioeconomic patterns. Some studies have found higher levels among lower income individuals, often linked with higher levels of smoking and environmental exposure, while others have reported minimal differences across groups (Tellez-Plaza et al., 2012). In children, these patterns may be less pronounced due to cumulative exposure and differences in behavioral risks. Importantly, these patterns are not independent of one another.

Environmental conditions, dietary behaviors, and social disadvantage frequently interact to shape exposure profiles. Households experiencing economic hardship may face increased exposure opportunities through multiple pathways simultaneously. Housing quality, neighborhood environments, access to food, and dietary choices can collectively influence exposure to environmental contaminants. For example, exposure to lead may be shaped by housing and infrastructure conditions, whereas mercury exposure may be influenced primarily

through dietary intake of fish and shellfish. These pathways are interconnected and highlight the importance of examining both environmental and dietary determinants of exposure.

Food Insecurity and Health. Food insecurity is a widely used indicator of economic hardship. It reflects the extent to which households have consistent access to enough food for an active and healthy life. In the U.S., food insecurity is measured using the U.S. Department of Agriculture (USDA) Household Food Security Survey Module, which captures a range of experiences related to constrained food access. This includes concerns about running out food, inability to afford balanced meals, and reductions in food intake due to financial limitations (Rabbitt et al., 2022). Based on responses to this tool, households are classified into four categories, full food security, marginal food security, low food security, and very low food security. These categories represent increasing severity of food related hardships. Notably, food insecurity prevalence increased following the COVID-19 pandemic in 2020, as many households experienced income instability, job loss, and disruptions in access to food (Rabbitt et al., 2022). This measure has been extensively validated and is widely used in public health research as a social determinant of health.

In recent years, food insecurity has remained a persistent issue in the U.S., impacting about 12 to 13% of households, with higher rates among households with children and among racial and ethnic minority groups (Rabbitt et al., 2022). Food insecurity is also not distributed equally across populations. National estimates consistently show higher rates of food insecurity among Black and Hispanic households compared with non-Hispanic White households (Rabbitt et al., 2022). These disparities reflect broader structural inequalities related to income, employment opportunities, housing conditions, neighborhood resources, and access to food. Due

to many of these same factors influencing environmental exposure opportunities, understanding racial and ethnic disparities is critical when examining food insecurity and toxic metal exposure.

Food insecurity reflects both economic constraints and broader social conditions. Food insecurity should not be viewed simply as another measure of poverty. Although the two concepts are closely related, food insecurity captures the experience of constrained access to food, and the tradeoffs households make when resources are limited. These experiences may influence exposure related behaviors and living conditions in ways that are not fully represented by income measures alone. Food insecurity may function as both an indicator of material hardship and a potential mechanism linking social disadvantage to environmental exposures. Food insecurity is closely linked to a range of adverse health outcomes across the life course. In children, food insecurity has been associated with poorer overall health, developmental delays, and increased risk of behavioral and mental health concerns (Shankar et al., 2017). These associations are thought to occur through multiple pathways, including diet quality, stress, and environmental conditions.

One of the most direct pathways linking food insecurity to health is through diet. Households experiencing food insecurity often face tradeoffs between cost, quantity, and quality of food. This can lead to less nutrient dense and variety of foods. Studies have shown that food insecurity is associated with lower intake of fruits, vegetables, and leaner proteins. In turn this leads to a higher reliance on energy dense low-cost foods (Cw et al., 2015). These dietary patterns can contribute to both undernutrition and overnutrition. This reflects the complex relationship between food insecurity and health outcomes such as chronic disease and obesity.

Dietary differences associated with food insecurity are also relevant for understanding exposure to environmental contaminants. For example, fish and shellfish are important sources

of beneficial nutrients but are also the primary dietary source of methyl mercury exposure (Kr et al., 2004). Seafood can be relatively expensive so households experiencing food insecurity may consume less fish, which can result in lower mercury exposure. At the same time, limited access to a variety of foods may increase reliance on lower cost staple foods, which may carry different exposure risks depending on production and environmental conditions. These patterns suggest that food insecurity may influence contaminant exposure through diet, although the direction of association varies through metal. Food insecurity is also closely linked to broader environmental conditions that shape exposure risk. Households experiencing food insecurity are more likely to live in housing with fewer resources for maintenance, increasing the likelihood of exposure to environmental hazards such as lead (Gundersen & Ziliak, 2015). These households may also be in neighborhoods with greater environmental burdens, including older infrastructure or proximity to pollution sources. In this way, food insecurity reflects not only constrained access to food but also broader structural disadvantages.

Conceptual Framework. Existing research demonstrates that exposure to environmental metals is socially patterned, but the pathways linking social conditions to exposure differ across metals. Lead exposure has been consistently associated with lower socioeconomic status, through environmental conditions like older housing (Benfer, 2024). Mercury exposure is primarily driven by diet, with higher levels observed among individuals who consume fish and shellfish more frequently, a pattern often associated with higher socioeconomic status (Cusack et al., 2017). Cadmium shows less consistent associations, showing its cumulative nature and multiple exposure sources, like tobacco smoke and diet (Tellez-Plaza et al., 2012). Taken together, these findings highlight that different metals reflect distinct exposure pathways like dietary behaviors and environmental conditions.

Despite this work, an important gap remains. Most prior studies have relied on traditional socioeconomic indicators such as income, poverty status, or educational attainment when examining environmental exposures. While these measures are valuable, they may not fully capture how social disadvantage is experienced in everyday life. Food insecurity may provide additional insight because it reflects both constrained access to food and the broader material conditions that influence diet, housing quality, and neighborhood environments. Furthermore, most prior studies have examined individual metals separately rather than evaluating multiple exposure pathways simultaneously. Far fewer studies have considered household food security as a primary exposure, even though it captures both economic constraint and its implications for diet and living conditions. In addition, relatively few analyses have used nationally representative biomarker data to examine how food security may simultaneously influence multiple exposure pathways, especially among children and adolescents. This gap limits understanding of how everyday material conditions translate into differences in exposures.

To address these gaps, this study is guided by a conceptual framework that conceptualizes food insecurity as a structural exposure capable of influencing toxic metal exposure through multiple pathways. Unlike traditional income based measures, food insecurity captures how economic hardship is experienced through food access, dietary constraints, and broader material conditions.

The first pathway is dietary. Food insecurity may influence food purchasing behaviors and access to foods associated with contaminant exposure. Fish and shellfish are the primary sources of methyl mercury exposure in the general population. Because seafood can be expensive, differences in affordability and consumption may contribute to variation in mercury exposure across food security groups (Gundersen & Ziliak, 2015). Under this pathway, lower

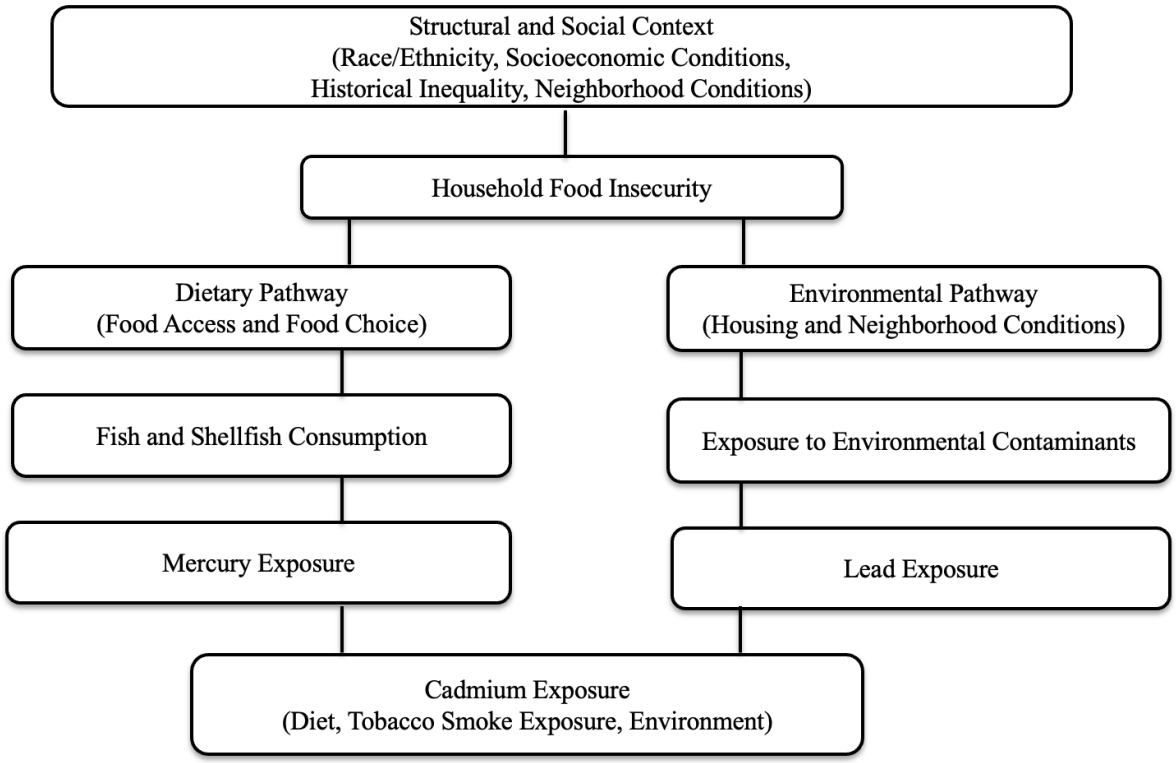
food security may be associated with lower mercury concentrations due to reduced seafood consumption.

The second pathway is environmental. Food insecurity frequently co-occurs with housing-related and neighborhood-level disadvantages that may increase opportunities for environmental exposures. These conditions include residence in older housing, aging infrastructure, environmental contamination, and reduced access to environmental resources (Jacobs et al., 2009). Under this pathway, lower food security may be associated with higher lead exposure due to greater exposure opportunities within the built environment.

Cadmium is at an intermediate position within this framework because exposure may reflect both environmental and dietary sources while also representing cumulative exposure over time. Associations between food insecurity and cadmium exposure are expected to be less clearly defined than those observed for lead and mercury.

These pathways are not independent. Rather, they operate within broader systems of social and structural inequality. Within this framework, race and ethnicity are conceptualized as indicators of social and structural context rather than biological characteristics. Differences in exposure across racial and ethnic groups reflect variation in housing quality, neighborhood environments, access to resources, dietary patterns, and historical inequities. Examining food security alongside race/ethnicity therefore allows for a more comprehensive understanding of how social conditions shape environmental exposures among children and adolescents as seen in Figure 1.

Figure 1. Conceptual Framework



METHODS

Data Source. This study uses data from the National Health and Nutrition Examination Survey (NHANES), a continuous, cross-sectional survey designed to assess the health and nutritional status of the United States population. NHANES is conducted by the National Center for Health Statistics (NCHS), part of the Centers for Disease Control and Prevention (CDC). NHANES utilizes a complex, multistage probability sampling design to produce nationally representative estimates (CDC, 2023). The survey combines in-home interviews with standardized physical examinations and laboratory assessment conducted in mobile examination centers (MECs), allowing for the collection of high-quality biomarker data alongside demographic, socioeconomic, and dietary information (NCHS, 2022).

For this analysis, data were drawn from two NHANES survey periods: 2017 to March 2020 (pre-pandemic) and August 2021 to August 2023 (post-pandemic). These cycles were

selected because they represent the most recent NHANES data releases that include measurements of blood metals, household food security, and key covariates of interest. The 2017 to March 2020 cycle was released as a pre-pandemic combined dataset due to disruptions in data collection during the COVID-19 pandemic, while data collection resumed in 2021 using updated sampling procedures (CDC, 2023). Combining these cycles increases statistical power and improves the precision of estimates while maintaining national representativeness when appropriate survey weights are applied.

The target population for this study is U.S. children aged 1 to 19 years old. This age range was selected to capture early life exposure to environmental contaminants, a critical period during which toxic metals such as lead, cadmium, and mercury can have lasting effects on neurodevelopment, growth, and overall health (Rehman et al., 2017). NHANES provides biomonitoring data on these metals through blood measurements, which are considered reliable indicators of recent exposure for mercury and lead, and of cumulative or chronic exposure for cadmium (NCHS, 2022). Restricting this analysis to individuals aged 1 to 19 years old also ensures consistency with NHANES laboratory subsamples for blood metals and aligns with this study's focus on child and adolescents.

Participants were included in the analytic sample if they had complete data on household food security, at least one blood metal measurement (lead, cadmium, total mercury, or methyl mercury), and all covariates included in the primary adjusted models. Individuals missing key exposure or outcome variables were excluded from the analyses. NHANES laboratory measures are collected on subsamples, therefore the analytic sample size varies across metals. For instance, methyl mercury is only measured in participants aged greater than or equal to 1 year in specific subsamples, resulting in slightly smaller sample sizes compared to total mercury. Similarly,

differences in participation in the MEC examination component contribute to variation in analytic sample sizes.

Additional exclusion criteria were applied to ensure valid and interpretable estimates. Participants with missing or unreliable dietary recall data were excluded from analyses examining dietary fish and shellfish intake. Pregnant adolescents were not explicitly excluded, as NHANES includes them in the general population samples, however, pregnancy status is indirectly accounted for through adjustment for age and other covariates. Extreme outliers in laboratory measurements were retained, as NHANES, utilizes rigorous quality control procedures and provides standardized biomarker data suitable for population level inferences (NCHS, 2022).

NHANES uses a complex sampling design involving clustering, stratification, and oversampling of certain population subgroups, including racial/ethnic minorities and low-income individuals, therefore, all analyses incorporated survey design variables and appropriate sample weights. When combining multiple survey cycles, weights were adjusted according to NCHS analytic guidelines to ensure that estimates remain representative of the U.S. population over the combined study periods (NCHS, 2026). This allows for valid inference while accounting for unequal probabilities of selection, nonresponse, and post stratification adjustments.

All data management and statistical analyses were conducted using R Version 2026.01.0+392. Survey weighted analyses were implemented using specialized statistical procedures designed for complex survey data, ensuring that variance estimates appropriately reflect the NHANES sampling design.

Exposure: Household Food Security. Household food security was the primary exposure of interest in this study and was assessed using the U.S. Department of Agriculture (USDA)

Household Food Security Survey Module that is implemented in NHANES. This instrument is a widely used, validated measure designed to capture the economic and social conditions that influence access to adequate food within households (USDA , 2000). Rather than measuring dietary intake directly, the food insecurity module assesses limited access to food due to financial limitations, integrating structural components.

In NHANES, food security is measured at the household level using the adult references module, which consists of a series of questions about experiences of food insufficiency and disrupted eating patterns over the past 12 months. These questions include concerns about running out of food, inability to afford balanced meals, reductions in food intake, and instances of skipping meals due to lack of resources. Responses are coded according to USDA guidelines to generate a raw score reflecting the severity of food insecurity, with higher scores indicating greater levels of food related hardship (NCHS 2017; NCHS; 2021).

Based on these responses, households are categorized into four standard levels of food security: full food security, marginal food security, low food security, and very low food security. Full food security indicates no reported indications of food access problems or limitations. Marginal food security reflects one or two reported concerns about food sufficiency. This can include anxiety about food supply but without substantial reductions in food intake. Low food security is characterized by reduced quality, desirability, or variety in food intake. Very low food security represents the most severe category, including multiple indications of disrupted eating patterns and reduced food intake among household members (Rabbitt et al., 2022).

For this analysis, food security was operationalized as a four level categorical variable, with full food security serving as the reference group in regression models. This categorization

keeps the ordinal structure of the exposure while allowing for nonlinear associations across the levels of severity. Treating food security as a categorical variable rather than continuous is consistent with prior epidemiological research and facilitates interpretation of results (Gundersen & Ziliak, 2015). Distinguishing between marginal and low food security is important as emerging evidence suggests that even marginal food insecurity, often overlooked in earlier research, may be associated with adverse health outcomes (Cook et al., 2013).

The decision to keep all four categories rather than collapsing them into binary food secure versus food insecure variables was driven by conceptual and empirical considerations. Conceptually, food insecurity is a continuum and collapsing categories may obscure important gradients in exposure severity. Empirically, preliminary analyses indicated variation in metal concentrations across four categories. Additionally, maintaining separate categories allows for the identification of threshold effects such as whether associations differ between moderate, low, and severe, very low, food insecurity.

It is important to note that the food security measure used in this study reflects the household level conditions rather than the individual level experiences. In households with children, the adult reference module may not fully capture child specific food insecurity, as adults often shield children from the most severe impacts of food scarcity (Nord, 2009). However, household food security remains a widely accepted proxy for children's exposure to food related hardship (Cook et al., 2013). The use of a standardized, nationally representative measure enhances compatibility with prior research and supports generalizability of findings.

Outcomes: Blood Metal Concentrations. The primary outcomes in this study were concentrations of four toxic metals measured in whole blood: lead (Pb), cadmium (Cd), total mercury (THg), and methyl mercury (MeHg). These biomarkers were selected due to their

established relevance to child and adolescent health and their availability in NHANES laboratory data. Each of these metals represents a distinct exposure pathway and toxicological profile allowing for a more comprehensive assessment of environmental exposures in children and adolescents.

Blood lead concentrations were measured in micrograms per deciliter (ug/dL), while blood cadmium, total mercury, and methyl mercury were measured in micrograms per liter (ug/L) consistent with NHANES laboratory reporting. These units reflect differences in expected concentration ranges and laboratory detection methods. Lead is typically reported in ug/dL due to its higher concentration levels in blood relative to other metals, whereas cadmium and mercury are present at lower concentrations and therefore reported in ug/L (NCHS, 2017; NCHS, 2021).

Laboratory measurements in NHANES are conducted using highly standardized quality-controlled procedures. Blood lead and cadmium concentrations are measured using inductively coupled plasma mass spectrometry (ICP-MS), a precise and sensitive method capable of detecting trace levels of metals in biological samples. Total mercury is also measured using ICP-MS, while methyl mercury is quantified using specialized analytical techniques that distinguish organic mercury species from total mercury (NCHS, 2017; NCHS, 2021). These methods undergo rigorous quality assurance including calibration and validation procedures to ensure accuracy and compatibility across cycles.

An important consideration in the analysis of biomarker data is the handling of values below the limit of detection (LOD). In NHANES, observations below the LOD are imputed using a standard substitution method in which values are assigned as the LOD divided by the square root of two. This approach is recommended by the NCHS to minimize bias while

preserving the distributional properties of the data (NCHS, 2017; NCHS, 2021). The proportion of values below the LOD varies by metal, with cadmium and methyl mercury being more likely to have low level detections compared to lead. Since NHANES provides these imputed values in the public use datasets no additional procedures were applied in this analysis.

Blood metal concentrations are typically right skewed with a small number of individuals exhibiting relatively high exposure levels. This skewness violates the assumptions of normality required for standard linear regression models and can disproportionately influence arithmetic means. To address this issue, all metal concentrations were log-transformed prior to analysis using the natural logarithm to help reduce skewness (Keene, 1995).

Following log transformation, results were summarized using geometric means rather than arithmetic means. The geometric mean is the exponentiated mean of the log transformed values and provides a measure of central tendency that's more appropriate for right skewed environmental exposure data. In environmental epidemiology and toxicology, geometric means are widely used because they better reflect exposure levels typically seen within a population and are less influenced by extreme values (Hornung & Reed, 1990).

In regression analyses, log transformed metal concentrations were modeled as continuous outcomes using survey weighted linear regression. Model coefficients were exponentiated to obtain geometric mean ratios (GMRs), which represent the relative difference in metal concentrations between exposure groups. For instance, a GMR greater than 1 indicates higher average concentrations relative to the reference group, while a GMR less than 1 indicates lower concentrations. This interpretation aligns with the log linear modeling framework and allows for an interpretation of results as percent differences. Using log transformations and GMRs is important in this study given the objective of comparing metal concentrations across levels of

food security. This approach is also consistent with prior NHANES based studies that have examined environmental exposures (Nguyen et al., 2020). These methodological choices are critical for accurately characterizing population level exposure patterns and for identifying potential disparities associated with social determinants such as food security.

Covariates. Covariates were selected based on prior knowledge of factors that may be related to both household food security and blood metal concentrations among children and adolescents. The goal of adjustment was to account for major demographic and socioeconomic factors that could confound the association between food security and metal exposure. The primary adjusted models included age group, sex, race/ethnicity, family income to poverty ratio, and survey cycle. Although food insecurity and poverty are closely related, they represent distinct constructs. Poverty reflects available economic resources, whereas food insecurity reflects how those resources translate into access to food and other material conditions. Because of this overlap, adjustment for poverty-income ratio (PIR) was undertaken cautiously and was intended to distinguish associations related to food security from those attributable to income alone. Adjusted estimates should be interpreted as associations between food security and metal exposure among households with similar income levels rather than estimates of the total effect of food insecurity. These covariates were chosen before the final model interpretation because each has a plausible relationship with both household food security and exposure opportunity.

Age was included because blood metal concentrations as well as exposure pathways can vary substantially across childhood and adolescence. Younger children may have different exposure risks than adolescents due to factors such as dietary patterns, hand to mouth behaviors, and time spent at home. Adolescents may have different dietary patterns and social environments that influence exposure to different metals, such as mercury exposure through fish intake or

cadmium exposure through environmental contexts. In NHANES, age is measured using RIDAGEYR. This is the participant's age in years at screening and for participants 19 years or younger, NHANES also provides age in months at examination, RIDEXAGM, when needed for pediatric analyses (NCHS, 2021). In this study, age was categorized into three developmental groups, 1 to 5 years old, 6 to 11 years old, and 12 to 19 years old. This grouping was chosen to distinguish early childhood, middle childhood, and adolescence while preserving sample size sufficiently within each category.

Sex was included as a demographic covariate because biological development, growth, body size, and behavior patterns can differ between female and male children and adolescents. In NHANES sex/gender is recorded using RIAGENDR, coded as male or female in the public use demographic files (NCHS, 2021). In this study, sex was treated as a binary covariate consistent with the NHANES public use coding. This variable was included to account for potential differences in exposure distribution and biomarker concentrations by sex, but it was not interpreted as a primary social determinant in the analysis. The focus of the study remained on household food security, socioeconomic status, and race/ethnicity.

Race/ethnicity was included because environmental exposure is socially patterned in the United States. Racial/ethnic categories often have differences in lived environments, housing conditions, diets, neighborhood contexts, and structural factors such as racism. NHANES race/ethnicity was measured using RIDRETH3, a recoded variable based on reported race and Hispanic origin that includes a separate non-Hispanic Asian category (NCHS, 2021). The categories used in this study were non-Hispanic White, non-Hispanic Black, Hispanic including Mexican American, non-Hispanic Asian, and other/multicultural. These categories were used

because they align with NHANES public use data and allow for comparison with prior NHANES based environmental health studies.

Race/ethnicity was not treated as a biological explanation for metal exposure. Race is a social classification, not a biological mechanism, and race/ethnic differences in exposure should be interpreted as reflecting structural and environmental conditions rather than inherent group differences. Epidemiologic literature has emphasized that race is often used as a proxy for exposure to racism and related social conditions but race itself does not cause health outcomes (Adkins-Jackson et al., 2021). Making this distinction is important because racialized disparities often reflect unequal housing quality, infrastructure, food systems, neighborhood environments, and policy histories. Race/ethnicity was therefore included as both a confounder in adjusted models and as a descriptive variable to examine disparities while interpretation focused on structural exposure pathways.

Socioeconomic position was measured using the family poverty income ratio (PIR), INDFMPIR, which is calculated as the ratio of family income to the federal poverty guideline for the relevant family size and year. NHANES describes PIR as a ratio of family income to poverty threshold or poverty guidelines (NCHS, 2021). A PIR below 1.0 indicates family income below the poverty threshold, while higher values indicate greater income relative to poverty. In this analysis PIR was included as a continuous covariate in the main regression models to account for socioeconomic confounding. PIR was categorized into three groups, less than 1.0, 1.0 to less than 2.0, and 2.0 or greater for descriptive tables and exploratory income stratified analyses.

PIR was included as a key socioeconomic covariate because household income is strongly associated with both food security and environmental exposure opportunities. Lower-income households may face increased environmental risks through housing conditions,

neighborhood environments, and resource limitations. However, food insecurity and PIR are conceptually and empirically related, as both reflect dimensions of socioeconomic disadvantage. Inclusion of PIR in adjusted models was intended to evaluate whether associations between food security and metal exposure persisted beyond differences in income alone. Since PIR may partially overlap with pathways through which food insecurity operates, adjusted estimates may represent conservative estimates of association.

Potential multicollinearity between food security and PIR was considered during model development because both variables capture aspects of socioeconomic disadvantage. However, food security and PIR were retained because they represent conceptually distinct dimensions of social conditions. PIR measures economic resources relative to federal poverty guidelines, whereas food insecurity reflects the lived experience of material hardship and food access. The inclusion of both variables allowed assessment of whether food security was associated with metal exposure independent of income differences.

The survey cycle was included to account for differences between the 2017 to March 2020 and 2021 to 2023 NHANES periods. These cycles differ in timing, sampling structure, and broader social contexts, including disruptions related to the COVID-19 pandemic (NCHS 2017). Adjusting for survey period helps control for temporal changes that may influence both food security and biomarker distributions.

The final adjustment set was intentionally limited to avoid overadjustment. Variables such as fish and shellfish intake and household smoking were not included in primary models because they may lie on the pathway between food security and metal exposure. For instance, fish intake is a primary determinant of mercury exposure and may be influenced by food access and affordability. Similarly, household smoking may contribute to cadmium exposure but also

reflects broader socioeconomic and environmental conditions. These variables were therefore evaluated in sensitivity and exploratory analyses rather than included in the main models.

Statistical analysis. All analyses were conducted using R Version 2026.01.0+392 and accounted for the complex survey design of NHANES. Since NHANES uses a multistage, stratified probability sampling design, standard statistical methods that assume simple random sampling are not appropriate. Instead, all analyses incorporated survey weights, strata, and primary sampling units (PSUs) to produce unbiased national estimates and correct standard errors (NCHS; 2021).

NHANES sampling design variables include strata SDMVSTRA and PSUs SDMVPSU, which reflect the hierarchical structure of the survey. Strata represent geographic and demographic groupings used during sampling, while PSUs represent clusters, these are often counties or groups of counties selected within strata. These design elements were incorporated using survey weighted procedures to ensure that variance estimation accounted for clustering and stratification (Lumley, 2010). Failing to account for these features can lead to underestimated standard errors and inflated statistical significance.

Appropriate sample weights were applied for all analyses. Since blood metals are measured in subsamples of NHANES participants, the phlebotomy examination weights WTPH2YR were used. When combining multiple NHANES cycles, weights must be adjusted according to NCHS analytic guidelines to maintain population representativeness. Following these guidelines, weights from each cycle were scaled by the number of cycles included such that the combined weights represent the average U.S. population over the pooled period (NCHS, 2021). This approach ensures that each survey period contributes equally to the analysis and estimates remain nationally representative.

Descriptive analyses were conducted using survey weighted methods to characterize the study population and to estimate biomarker distributions. Weighted geometric means and corresponding 95% confidence intervals were calculated for each metal overall and by levels of food security and race/ethnicity. Geometric means were used rather than arithmetic means because metal concentrations are right skewed and geometric means provide a more appropriate measure of central tendency for log-normally distributed data (Hornung & Reed, 1990). Confidence intervals for geometric means were derived by calculating the mean and standard error on the log scale and then exponentiating the results back to the original scale.

The primary analytic approach used survey weighted linear regression models with log transformed metal concentrations as outcomes. Specifically, the natural logarithm of each metal concentration was modeled as a function of food security status and covariates. This log linear modeling framework allows regression coefficients to be interpreted in terms of proportional change. After model fitting, coefficients were exponentiated to obtain geometric mean ratios (GMRs) which represent the ratio of expected mean concentrations between comparison groups.

For example, a GMR of 1.10 indicates that the geometric mean concentration in a given exposure group is 10% higher than the reference group, while a GMR of 0.90 indicates a 10% lower concentration. Results were reported as GMRs with 95% confidence intervals and corresponding p values, statistical significance was assessed based on whether confidence intervals excluded 1.0.

Model specification followed a sequential adjustment strategy. Initial models included household food security as the primary exposure. Subsequent models adjusted for age group and sex, followed by adjustment for race/ethnicity. Final models additionally adjusted for PIR and survey cycle. This sequential approach allowed assessment of how associations changed

following adjustment for demographic and socioeconomic factors and provided insight into the extent to which observed associations may reflect broader socioeconomic conditions.

Handling of missing data was based on a complete case approach for each analysis. Participants were included if they had non-missing data on the exposure, outcome, and all covariates included in the model. NHANES laboratory measures are collected in subsamples, and not all participants complete every component of the survey so therefore sample sizes vary across outcomes and models. The extent of missingness was evaluated descriptively and is reported in the appendix. Although complete case analysis may introduce bias if missingness is not random, it is commonly used in NHANES analyses when the proportion of missing data is moderate and when complex survey design considerations limit the feasibility of imputation (Little & Rubin, 2019). Given the study design and available data, this approach was considered appropriate with the limitation acknowledged in the discussion.

In addition to the primary analyses, several exploratory analyses that were not the primary focus of the study were conducted to better understand potential pathways. First, dietary sensitivity analyses were conducted for mercury outcomes by including indicators of fish and shellfish consumption. Fish intake is a well-established source of methyl mercury exposure, and differences in seafood consumption may explain variation in mercury levels across socioeconomic groups (Kr et al., 2004). Models including dietary variables were used to assess whether observed associations between food security and mercury were reduced after accounting for fish and shellfish consumption. These analyses were restricted to participants with reliable dietary recall data.

Second, interaction analyses were conducted to explore whether associations between food security and metal concentrations differed across racial and ethnic groups. Since food

insecurity and socioeconomic status are closely related constructs, interaction analyses focused primarily on race/ethnicity, which may reflect differences in housing conditions, environmental exposures, dietary practices, and other structural factors influencing exposure opportunities. Interaction terms between food security and race/ethnicity, as well as between food security and poverty income ratio categories were added to regression models. Statistical significance of interaction terms was evaluated using Wald tests. Interaction analyses were exploratory and intended to evaluate potential effect modification rather than establish causal differences between groups. Attention was given to racial and ethnic variation because prior research has documented substantial disparities in environmental exposures across population groups.

Finally, additional sensitivity analyses were conducted to evaluate the robustness of findings. These included models using alternative specifications of food security, models stratified by income categories, and models adjusting for household smoking exposure for cadmium outcomes. These analyses were used to assess whether results were consistent across different modeling choices and to identify potential pathways linking food insecurity to metal exposure.

It is important to note because food insecurity and PIR capture related aspects of socioeconomic disadvantage, some degree of overlap between these measures is expected. Consequently, adjustment for PIR may attenuate associations between food insecurity and metal exposure if income lies on part of the pathway linking food insecurity to environmental exposures. Findings should therefore be interpreted with consideration of the potential for conservative estimation resulting from adjustment for closely related socioeconomic variables.

RESULTS

Sample Characteristics. The analytic sample consisted of children and adolescents aged 1 to 19 years old from the combined NHANES 2017 to March 2020 and 2021 to 2023 cycles, overall sample N=7,062 varying by biomarker, approximately n=4,552 for lead, n=5,497 for cadmium and total mercury, and n=1,674 for methyl mercury. Sample size varied across analyses depending on the availability of biomarker data and covariates, but overall characteristics of the study population are presented in Table 1. Survey Weights were applied to all estimates to reflect the U.S. population.

Table 1. Survey-Weighted Sample Characteristics by Food Security Among U.S. Children and Adolescents Aged 1-19 years, NHANES 2017-March 2020 and August 2021-August 2023

Characteristic	Overall (N=7,062)	Full	Marginal	Low	Very low
Age group					
1-5	25.0% (n=1884)	24.9% (n=1023)	24.4% (n=315)	23.5% (n=232)	28.5% (n=205)
6-11	31.4% (n=2355)	31.3% (n=1231)	31.0% (n=401)	33.5% (n=356)	29.3% (n=237)
12-19	43.7% (n=2823)	43.8% (n=1518)	44.6% (n=457)	42.9% (n=376)	42.2% (n=308)
Sex					
Male	51.1% (n=3597)	50.7% (n=1912)	53.8% (n=623)	51.3% (n=486)	51.0% (n=375)
Female	48.9% (n=3465)	49.3% (n=1860)	46.2% (n=550)	48.7% (n=478)	49.0% (n=375)
Race/ethnicity					
Non-Hispanic White	48.8% (n=2366)	59.3% (n=1604)	33.8% (n=277)	29.6% (n=197)	35.2% (n=194)
Non-Hispanic Black	12.6% (n=1661)	9.5% (n=683)	19.0% (n=374)	15.7% (n=257)	18.2% (n=232)
Hispanic (including Mexican American)	25.3% (n=1818)	17.4% (n=732)	35.5% (n=367)	44.9% (n=385)	34.6% (n=222)
Non-Hispanic Asian	5.8% (n=551)	6.4% (n=380)	4.8% (n=61)	4.2% (n=49)	1.6% (n=15)
Other / Multiracial	7.5% (n=666)	7.4% (n=373)	6.9% (n=94)	5.7% (n=76)	10.4% (n=87)
Poverty-income ratio (mean, SD)	2.59 (1.67) (n=6257)	3.21 (1.62) (n=3575)	1.73 (1.18) (n=1066)	1.46 (1.08) (n=894)	1.16 (0.92) (n=722)
Poverty-income ratio category					
<1.0	22.4% (n=1887)	12.0% (n=627)	33.6% (n=453)	41.5% (n=404)	51.8% (n=403)
1.0-<2.0	22.8% (n=1637)	16.8% (n=734)	32.8% (n=345)	34.3% (n=321)	34.0% (n=237)
≥2.0	54.8% (n=2733)	71.2% (n=2214)	33.6% (n=268)	24.3% (n=169)	14.3% (n=82)
Household Smoking					
No household smoker	73.8% (n=4635)	80.9% (n=2941)	64.1% (n=703)	63.5% (n=596)	53.3% (n=389)
Any household smoker	26.2% (n=2031)	19.1% (n=829)	35.9% (n=470)	36.5% (n=368)	46.7% (n=361)
Survey period					
2017-March 2020	61.5% (n=5228)	63.0% (n=2793)	64.0% (n=919)	61.3% (n=698)	57.0% (n=545)
2021-August 2023	38.5% (n=1834)	37.0% (n=979)	36.0% (n=254)	38.7% (n=266)	43.0% (n=205)

Note: Values are survey-weighted percentages or weighted mean (SD), estimated using pooled NHANES blood-analyte weights.

Clear socioeconomic gradients were observed across levels of household food security. Children living in households with lower food security were more likely to have lower family income, as measured by PIR. Mean PIR generally decreased from approximately 3.21 in fully food secure households to 1.16 in very low food security households, indicating a strong relationship between economic disadvantage and food insecurity. In addition, children in lower food security households were more likely to live in families below the federal poverty threshold and less likely to be in higher income categories, with a PIR of less than or equal to 1 being more common in very low food security households. These patterns are consistent with the conceptualization of food insecurity because of constrained economic resources.

The strong gradient observed between food security and PIR also demonstrate substantial overlap between these measures. Mean PIR declined from 3.21 among fully food secure households to 1.16 among very low food security households. Although this relationship was expected, it reinforces the importance of interpreting adjusted analyses as estimates of food security independent of income rather than estimates of the total socioeconomic effect associated with food insecurity.

Differences in demographic composition were also evident across food security categories. The distribution of race and ethnicity varied substantially, with children from Hispanic households comprising approximately 44.9% of the low food security group and 34.6% of the very low food security group, while non-Hispanic White children were more likely to be fully food secure, 59.3%. Non-Hispanic White children were more likely to reside in households with full food security. Non-Hispanic Asian children showed a distinct distribution, with relatively lower representation in the most severe food insecurity categories. These patterns reflect well documented disparities in food insecurity across racial and ethnic groups in the

United States and highlight the importance of considering structural and socioeconomic factors when examining environmental exposures (Rabbitt et al., 2022).

These findings demonstrate that food insecurity was not distributed equally across the study population. Hispanic and non-Hispanic Black children were disproportionately represented in lower food security categories, while non-Hispanic White children were more likely to reside in fully food secure households. These patterns are consistent with national estimates of food insecurity and highlight the importance of considering race/ethnicity as part of the broader social and structural context influencing environmental exposures.

Household smoking exposure also differed across levels of food security. Children living in households with lower food security were more likely to be exposed to cigarette smoke in the home compared to those in food secure households. The prevalence of household smoking exposure increased from approximately 19.1% in fully food secure households to 46.7% in very low food security households, suggesting a clustering of risk factors within socioeconomically disadvantaged households.

Age and sex distributions were relatively similar across food security categories, although minor differences were observed. Younger children were somewhat more represented in certain categories, but no strong age gradient was evident. The proportion of males, about 51%, and females was generally balanced across groups, indicating that sex differences were unlikely to confound associations between food security and metal concentrations in descriptive analyses.

Descriptive Metal Levels. Survey weighted geometric mean concentrations of blood lead (Pb), cadmium (Cd), total mercury (THg), and methyl mercury (MeHg) across levels of household food security are presented in Table 2 and Figure 2. These estimates are unadjusted and reflect population level differences in biomarker concentrations by food security status.

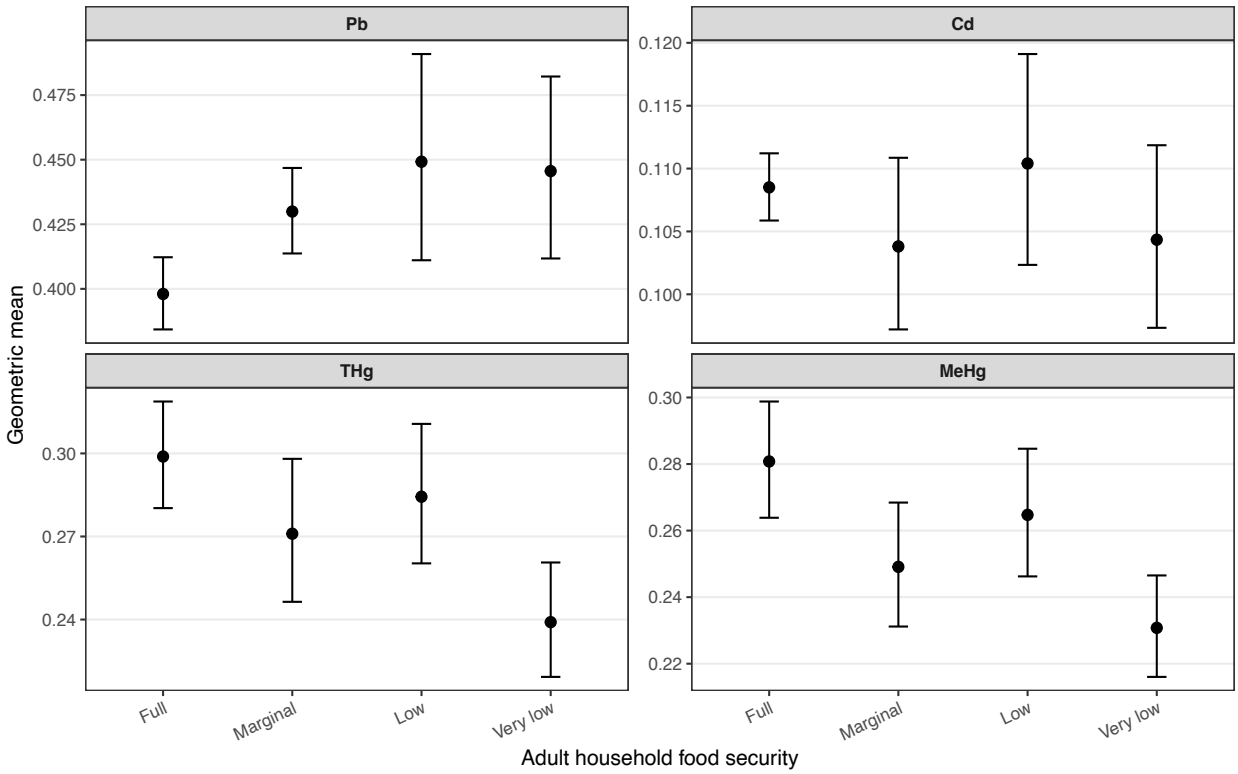
Geometric means were used because all metal biomarkers were right skewed and this measure better represents the central tendency of environmental exposure data.

Table 2. Weighted Geometric Means of Blood Metals by Household Food Security

Food security	Unweighted n	Geometric mean (95% CI)
Blood lead (ug/dL)		
Full	2560	0.40 (0.38, 0.41)
Marginal	794	0.43 (0.41, 0.45)
Low	666	0.45 (0.41, 0.49)
Very low	532	0.45 (0.41, 0.48)
Blood cadmium (ug/L)		
Full	3071	0.11 (0.11, 0.11)
Marginal	979	0.10 (0.10, 0.11)
Low	798	0.11 (0.10, 0.12)
Very low	649	0.10 (0.10, 0.11)
Total mercury (ug/L)		
Full	3071	0.30 (0.28, 0.32)
Marginal	979	0.27 (0.25, 0.30)
Low	798	0.28 (0.26, 0.31)
Very low	649	0.24 (0.22, 0.26)
Methyl mercury (ug/L)		
Full	3035	0.28 (0.26, 0.30)
Marginal	973	0.25 (0.23, 0.27)
Low	790	0.26 (0.25, 0.28)
Very low	642	0.23 (0.22, 0.25)

Note: Survey-weighted geometric mean concentrations of blood lead, cadmium, total mercury, and methyl mercury by adult household food security.

Figure 2. Weighted Geometric Means of Blood Metals by Household Food Security



Note: Survey-weighted geometric mean blood metal concentrations by adult household food security. These are descriptive, unadjusted estimates, adjusted associations are presented in Table 4 and Figure 4. Mercury patterns should be interpreted alongside the dietary sensitivity models.

Blood lead concentrations showed modest differences across food security categories. Among children living in households with full food security, the weighted geometric mean blood lead concentration was approximately 0.40 ug/dL. This value increased slightly to 0.43 ug/dL among those with marginal food security and to 0.45 ug/dL among those with low food security. Children in households with very low food security had similar or slightly higher levels compared to the low food security group, with geometric means of about both 0.45ug/dL. Overall, these values indicate a gradual increase in blood lead concentrations as food security worsens, although the magnitude of the differences is relatively small.

Blood cadmium concentrations were relatively stable across all levels of food security. The weighted geometric mean for cadmium was about 0.11 ug/L among children in fully food secure households and remained close to this value across marginal, low, and very low food secure groups. Differences between categories were minimal, generally within a narrow range of 0.10 to 0.12 ug/L. There was no clear pattern of increasing or decreasing cadmium concentrations across food security levels in these descriptive analyses.

Mercury patterns were different from lead and cadmium. Total mercury concentrations were highest among children living in fully food secure households and generally decreased with worsening food security. The geometric mean for total mercury was about 0.30 ug/L in the full food security group, compared to 0.27 ug/L in the marginal group, 0.28 ug/L in the low food security group, and 0.24 ug/L in the very low food security group. This pattern indicates an overall decline in total mercury concentrations with worsening food security, although values are not strictly the same across all categories.

A similar pattern was observed for methyl mercury, which represents the organic form of mercury most strongly associated with dietary exposure. Among children in fully food secure households, the geometric mean methyl mercury concentration was approximately 0.28 ug/L. This decreased to around 0.25 ug/L for marginal food security, 0.26 ug/L for low food security, and about 0.23 ug/L for very low food security. The decrease in methyl mercury concentrations across categories was somewhat more pronounced than that observed for total mercury, although both biomarkers followed the same general trend.

Figure 2 illustrates these patterns, with separate panels for each metal. The figure shows that while differences in lead concentrations across food security categories are modest, the gradient is consistent in direction. Cadmium concentrations appear largely unchanged across

categories, with overlapping confidence intervals. In contrast, both total mercury and methyl mercury show a clear downward trend as food security decreases, with the highest concentrations observed in the fully food secure group and the lowest concentrations in the very low food security group.

Confidence intervals for these estimates, shown in Table 2 and Figure 2, overlap across many categories, particularly for lead and cadmium, reflecting variability in the data and relatively small differences between groups. For mercury biomarkers, confidence intervals are narrower and show less overlap between the highest and lowest food security categories, consistent with the more distinct gradient observed for these outcomes.

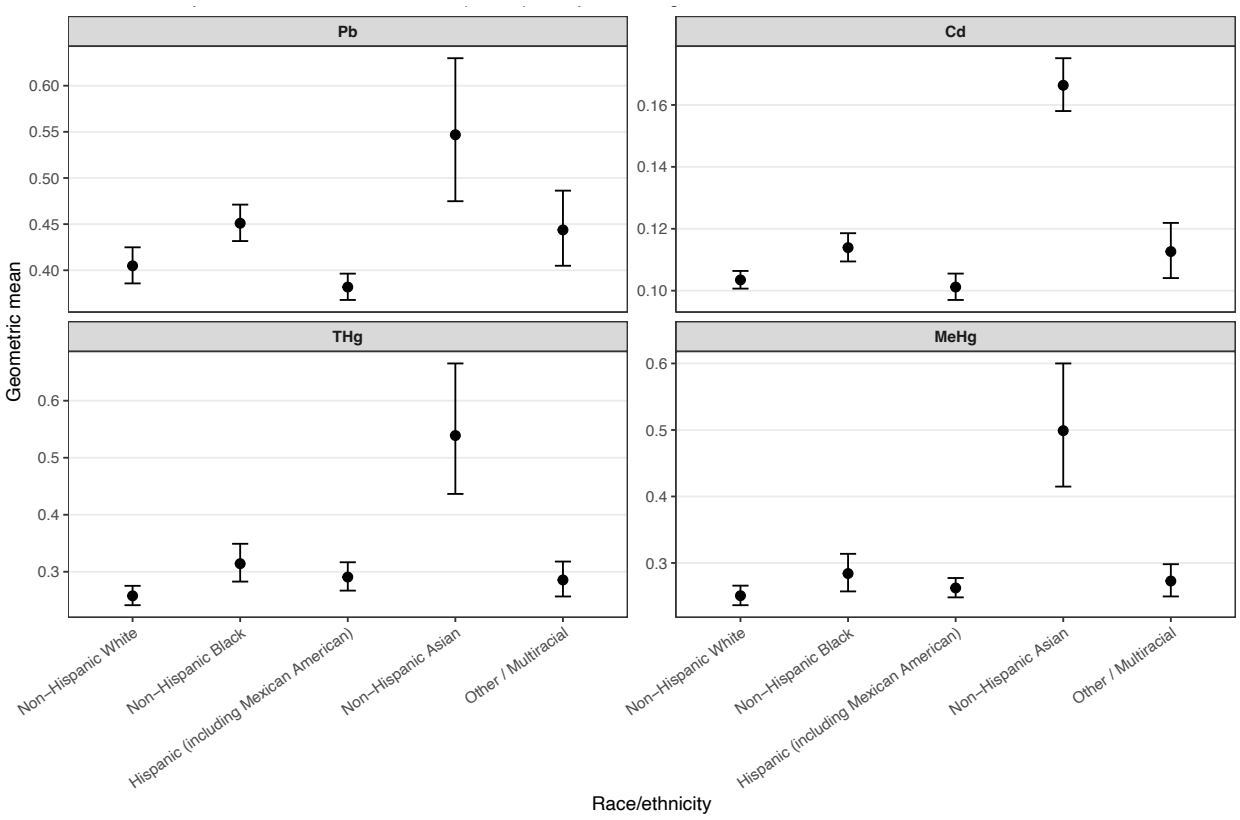
Race/Ethnicity Differences. Survey weighted geometric mean concentrations of blood lead (Pb), cadmium (Cd), total mercury (THg), and methyl mercury (MeHg) by race and ethnicity are presented in Table 3 and Figure 3. These estimates are unadjusted and describe differences in exposure patterns across population groups.

Table 3. Weighted Geometric Means of Blood Metals by Race/Ethnicity

Race/ethnicity	Unweighted n	Geometric mean (95% CI)
Blood Lead (ug/dL)		
Non-Hispanic White	1622	0.40 (0.39, 0.42)
Non-Hispanic Black	1019	0.45 (0.43, 0.47)
Hispanic (including Mexican American)	1348	0.38 (0.37, 0.40)
Non-Hispanic Asian	389	0.55 (0.47, 0.63)
Other / Multiracial	450	0.44 (0.40, 0.49)
Blood Cadmium (ug/L)		
Non-Hispanic White	1981	0.10 (0.10, 0.11)
Non-Hispanic Black	1280	0.11 (0.11, 0.12)
Hispanic (including Mexican American)	1572	0.10 (0.10, 0.11)
Non-Hispanic Asian	436	0.17 (0.16, 0.18)
Other / Multiracial	554	0.11 (0.10, 0.12)
Total Mercury (ug/L)		
Non-Hispanic White	1981	0.26 (0.24, 0.28)
Non-Hispanic Black	1280	0.31 (0.28, 0.35)
Hispanic (including Mexican American)	1572	0.29 (0.27, 0.32)
Non-Hispanic Asian	436	0.54 (0.44, 0.67)
Other / Multiracial	554	0.29 (0.26, 0.32)
Methyl Mercury (ug/L)		
Non-Hispanic White	1960	0.25 (0.24, 0.27)
Non-Hispanic Black	1263	0.28 (0.26, 0.31)
Hispanic (including Mexican American)	1561	0.26 (0.25, 0.28)
Non-Hispanic Asian	432	0.50 (0.41, 0.60)
Other / Multiracial	544	0.27 (0.25, 0.30)

Note: Survey-weighted geometric mean concentrations of blood metals by race/ethnicity.

Figure 3. Weighted Geometric Means of Blood Metals by Race/Ethnicity



Note: Survey-weighted geometric mean concentrations of blood metals by race/ethnicity.

Clear differences in blood metal concentrations were observed across racial and ethnic groups. For lead, non-Hispanic Black children had higher geometric mean concentrations compared to other groups. The weighted geometric mean blood lead level among non-Hispanic Black children was approximately 0.45 ug/dL, compared to about 0.40 ug/dL among non-Hispanic White children. Hispanic children had similar values or slightly below those observed among non-Hispanic White children, generally 0.38 ug/dL. Non-Hispanic Asian children had the highest lead concentrations at 0.55 ug/dL. Overall, the differences in lead concentrations were modest in magnitude but showed a consistent pattern, with higher values observed among non-Hispanic Black children and non-Hispanic Asian children.

Blood cadmium concentrations also varied across racial and ethnic groups. Non-Hispanic Black children again had slightly higher geometric mean cadmium levels compared to other groups, with values around 0.11 ug/L. Non-Hispanic White children had slightly lower concentrations, generally around 0.10 to 0.11 ug/L. Hispanic children had levels similar to non-Hispanic White children, while non-Hispanic Asian children had values that were comparable or slightly higher, though differences were relatively small overall. As with lead, the differences in cadmium concentrations across groups were modest but consistent.

Mercury concentrations showed a different pattern across racial/ethnic groups. Non-Hispanic Asian children had substantially higher levels of mercury and methyl mercury compared to all other groups. The geometric mean total mercury concentration among non-Hispanic Asian children was about 0.50 to 0.55 ug/L, nearly double the levels observed among non-Hispanic White children, whose mean total mercury concentration was around 0.26 ug/L. Hispanic children had intermediate values, generally around 0.29 ug/L, while non-Hispanic black children had slightly higher levels, about 0.31 ug/L.

A similar pattern was observed for methyl mercury. Non-Hispanic Asian children had the highest geometric mean methyl mercury concentrations, about 0.48 to 0.52 ug/L, compared to around 0.25 ug/L among non-Hispanic White children. Hispanic children again had intermediate values, while non-Hispanic Black children had slightly higher concentrations overall at 0.28ug/L. The differences in methyl mercury across groups were larger in magnitude than those observed for lead and cadmium and are clearly visible in Table 3 and Figure 3.

Figure 3 illustrated these differences across metals and racial/ethnic groups. The figure used separate panels for each metal, allowing for a clearer visualization of within metal differences. For mercury biomarkers the concentrations among non-Hispanic Asian children are

particularly evident, with values consistently exceeding those observed in other groups. For lead and cadmium, differences are less pronounced but still show higher concentrations among non-Hispanic Black children relative to other groups.

Confidence intervals for these estimates overlap across some groups, particularly for lead and cadmium, indicating variability and relatively small differences in absolute levels. However, for mercury biomarkers, the separation between non-Hispanic Asian children and other groups is more distinct with less overlap in confidence intervals, reflecting larger differences in exposure. These results indicate that patterns of metal exposure differ across racial and ethnic groups, with higher lead and cadmium concentrations observed among non-Hispanic Black children and higher mercury concentrations observed among non-Hispanic Asian children.

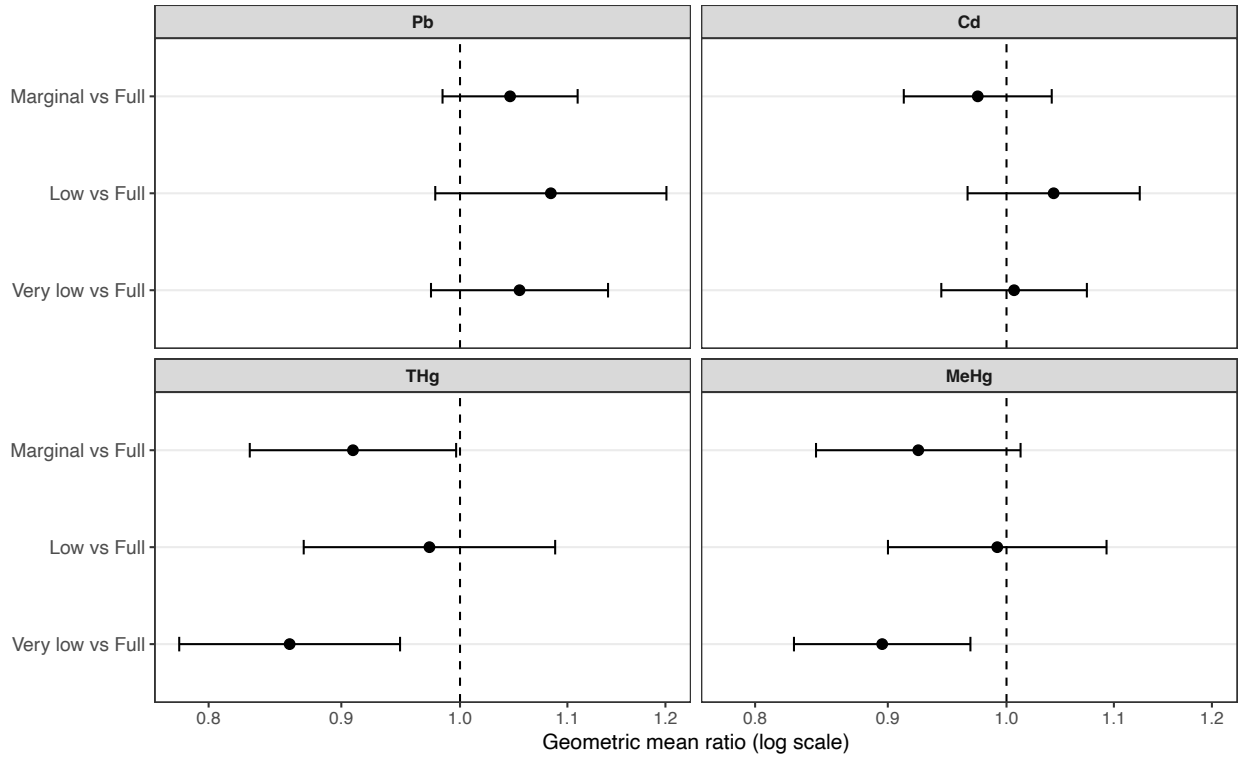
Adjusted Models. Adjusted associations between household food security and blood metal concentrations are presented in Table 4 and Figure 4. These models account for age group, sex, race/ethnicity, poverty income ratio (PIR), and survey cycle. Results are expressed as geometric mean ratios (GMRs) comparing each level of food security to the reference category of full food security.

Table 4. Adjusted Associations Between Adult Household Food Security and Blood Metals

Comparison	Unweighted n	df	GMR (95% CI)	Difference vs full	p-value
Blood lead					
Marginal vs Full	4289	40	1.05 (0.98, 1.11)	+4.5%	0.140
Low vs Full	4289	40	1.08 (0.98, 1.20)	+8.4%	0.119
Very low vs Full	4289	40	1.05 (0.97, 1.14)	+5.4%	0.179
Blood cadmium					
Marginal vs Full	5171	40	0.97 (0.91, 1.04)	-2.5%	0.433
Low vs Full	5171	40	1.04 (0.97, 1.13)	+4.3%	0.272
Very low vs Full	5171	40	1.01 (0.94, 1.07)	+0.7%	0.832
Total mercury					
Marginal vs Full	5171	40	0.91 (0.83, 1.00)	-9.1%	0.042
Low vs Full	5171	40	0.97 (0.87, 1.09)	-2.7%	0.622
Very low vs Full	5171	40	0.86 (0.78, 0.95)	-14.0%	0.004
Methyl mercury					
Marginal vs Full	5116	40	0.92 (0.84, 1.01)	-7.5%	0.088
Low vs Full	5116	40	0.99 (0.90, 1.09)	-0.8%	0.864
Very low vs Full	5116	40	0.90 (0.83, 0.97)	-10.4%	0.007

Note: Adjusted survey-weighted log-linear regression models estimating associations between adult household food security and blood metal concentrations. Models adjusted for age group, sex, poverty-income ratio, race/ethnicity, and survey period. Values are geometric mean ratios; percent difference is calculated as (GMR - 1) × 100. Estimates are cross-sectional associations.

Figure 4. Adjusted Associations Between Household Food Security and Blood Metals



Note: Adjusted survey-weighted geometric mean ratios for adult household food security categories compared with full food security. Models are adjusted for age group, sex, poverty-income ratio, race/ethnicity, and survey period. The dashed vertical line indicates no difference (GMR = 1); estimates whose confidence intervals cross 1 should not be interpreted as statistically significant.

After adjustment, blood lead concentrations showed modest increases with worsening food security, although these differences were not statistically significant. Compared with children living in fully food secure households, those in marginal, low, and very low food security households exhibited GMRs ranging from approximately 1.05 to 1.08. While the direction of association remained consistent with the hypothesis that lower food security may be associated with greater environmental exposure risk, adjustment for demographic and socioeconomic covariates substantially attenuated observed differences. Given the strong relationship between food insecurity and PIR, part of this attenuation may reflect adjustment for socioeconomic pathways that contribute to both food insecurity and lead exposure.

There was little evidence of an association between food security and blood cadmium concentrations in adjusted models. Across all food security categories, GMRs were close to 1.0, with values generally ranging from about 0.97 to 1.04. Confidence intervals were narrow and consistently included 1.0, indicating no statistically significant differences between food security groups. These findings are consistent with descriptive analyses, which showed minimal variation in cadmium levels across categories, and suggest that cadmium exposure does not vary systematically by food security status in this population.

Results for mercury differed from those observed for lead and cadmium. After adjustment, both total mercury (THg) and methyl mercury (MeHg) concentrations were significantly lower among children in more food insecure households compared to those with full food security. For total mercury, children in low food security households had GMRs of approximately 0.97 relative to the reference group, while those in very low food security households had GMRs around 0.86. These estimates correspond with reductions of about 3% for low food security and about 14% for very low food security. Confidence intervals for the very low food security group did not include 1.0 indicating statistically significant differences and estimates for low food security were not statistically significant

A similar pattern was observed for methyl mercury. Children in low food security households had GMRs of approximately 0.99, while those in very low food secure households had GMRs in the range of 0.90. These values indicate reductions of about 10 to 20% in methyl mercury concentrations relative to children in fully food secure households. As with total mercury, confidence intervals for the very low food security group excluded 1.0, while those for low food security included 1.0

Figure 4 presents these adjusted associations, with GMRs plotted on a logarithmic scale and a reference line at 1.0 indicating no difference. For lead and cadmium, point estimates are clustered near the null value, with confidence intervals crossing the reference line across all categories. For both mercury biomarkers, point estimates for low and very low food security fall below 1.0, however, only the very low food security category shows confidence intervals that do not cross 1.0.

Exploratory analyses. Additional analyses were conducted to explore potential pathways and heterogeneity in the association between household food security and blood metal concentrations, these analyses were not part of the primary analytic plan and are here as exploratory.

Dietary variables were strongly associated with mercury biomarkers. In models including indicators of fish and shellfish consumption, both total mercury (THg) and methyl mercury (MeHg) concentrations were substantially higher among children who reported recent seafood intake. Specifically, children who consumed fish in the past 30 days had approximately 65 to 70% higher total mercury concentrations compared to those who did not, THg GMR= 1.67, 95% CI: 1.54 to 1.81. A similar pattern was observed for methyl mercury, with GMRs around 55 to 60% higher, GMR 1.58, 95% CI 1.48 to 1.69. Shellfish consumption showed a similar but somewhat smaller association (GMR 1.31 for total mercury and 1.25 for methyl mercury). These results suggest that seafood intake is a major predictor of mercury exposure in this population.

When dietary variables were added to models examining food security and mercury, the magnitude of the association between food insecurity and lower mercury concentrations was reduced but not eliminated. For example, the GMR for very low food security compared to full food security for total mercury increased from about 0.86 in the primary adjusted model to

values closer to 0.91 after adjusting for fish consumption. A similar reduction was observed for methyl mercury. Although confidence intervals remained below or near 1.0 in some models, the reduction in effect size suggests that differences in seafood consumption may account for part of the observed variation in mercury levels across food security categories.

Exploratory interaction analyses were conducted to assess whether associations between food security and metal concentrations differed by race/ethnicity. Interaction terms between food security and race/ethnicity were not statistically significant for any of the metals examined. Point estimates varied slightly across groups, but confidence intervals were wide and overlapped substantially. These results suggest that the overall association between food security and metal concentrations did not differ meaningfully across racial and ethnic groups within the limits of the available sample size.

Additional analyses stratified by income were conducted to examine whether associations between food security and lead concentrations differed across levels of socioeconomic position. Within lower income strata, PIR less than 1.0, children in low and very low food security households had somewhat higher lead concentrations compared to those with full food security, with a GMR generally of 1.11. In the middle-income group (PIR 1.0 to <2.0), estimates were below the null, GMR 0.95, while in higher income households (PIR >=2.0), estimates were elevated 1.15. However, confidence intervals in these stratified models were wider due to smaller sample sizes, and most estimates were not statistically significant. As a result, these findings should be interpreted cautiously. The interaction between food insecurity and income was not statistically significant (p=0.076).

An exploratory analysis examining early life feeding practices was conducted, including breastfeeding duration and timing of formula introduction, in relation to blood metal

concentrations among children aged 1 to 6 years. These analyses were based on smaller subsamples and should be interpreted cautiously. Breastfeeding duration was not clearly associated with blood lead or mercury biomarkers, compared to children who were not breastfed, those with short (1 to 30 days), medium (31 to 180 days), or longer (greater than or equal to 180 days) breastfeeding duration had GMRs close to 1.0 for lead, total mercury, and methyl mercury, with confidence intervals that included the null. A modest association was observed for cadmium, where longer breastfeeding duration (greater than or equal to 180 days) was associated with slightly higher concentrations, GMR = 1.13, 95% CI: 1.04 to 1.22, while shorter durations showed smaller, non-significant differences. Formula timing showed a different pattern, with early formula introduction, less than or equal to 30 days, associated with lower blood lead, GMR= 0.76, 95% CI: 0.59 to 0.98) and lower cadmium concentrations (GMR= 0.88, 95% CI: 0.80 to 0.96) compared to later or no early formula exposure, associations with mercury biomarkers were minimal, with GMRs near 1.0 and confidence intervals that included the null. Overall, these results were not consistent across metals and should be interpreted cautiously given the smaller sample sizes and retrospective measurement of feeding practices.

DISCUSSION

Summary of Findings. Overall, the findings suggest that patterns of metal exposure differ across levels of food security, with distinct trends observed for each metal. These differences were modest for some outcomes and more pronounced for others, highlighting the importance of considering both environmental and dietary pathways when interpreting exposure patterns. Taken together, these findings suggest that the relationship between food security and toxic metal exposure differs across exposure pathways. Associations were strongest for mercury, which is primarily acquired through diet, and weaker for lead and cadmium after adjustment for

demographic and socioeconomic factors. These patterns are consistent with the conceptual framework proposed in this study and support the idea that food insecurity may influence environmental exposures through both dietary and environmental mechanisms.

For lead, descriptive analyses showed slightly higher concentrations among children living in households with lower food security, and this pattern remained in adjusted models. However, after accounting for age, sex, race/ethnicity, income, and survey period, these differences were small and not statistically significant. The direction of association was consistent across models, suggesting a possible relationship between food insecurity and increased lead exposure, but the evidence was not strong enough to support a definitive conclusion. These findings suggest that while there may be underlying differences in exposure, they are relatively modest within the range observed in this population.

Although adjusted associations between food insecurity and blood lead concentrations were not statistically significant, the direction of association remained consistent with the study hypothesis. Children living in households with lower food security generally exhibited slightly higher lead concentrations than children living in fully food secure households. One possible explanation for the attenuation of these associations is the inclusion of PIR in adjusted models. Food insecurity and income are closely related, therefore adjustment for PIR may have removed part of the broader socioeconomic pathway through which food insecurity influences exposure opportunities. As a result, adjusted estimates may represent conservative estimates of association.

Cadmium concentration showed a little variation across levels of food security in both descriptive and adjusted analyses. Estimates were consistently close to the null and there was no clear pattern of increasing or decreasing exposure across categories. This suggests that cadmium

exposure, at least measured in blood, may not be strongly associated with household food security in this population. The lack of association was consistent across multiple models and sensitivity analyses, indicating that this finding was relatively robust.

Mercury biomarkers showed a different pattern. Both total mercury and methyl mercury concentrations were lower among children living in households with lower food security, and these differences persisted after adjustment for demographic and socioeconomic factors. The decrease in mercury concentrations was consistent across categories of food insecurity and was more pronounced than the patterns observed for lead or cadmium. Exploratory analyses further indicated that fish and shellfish consumption was strongly associated with mercury levels, and that adjusting for dietary intake reduced the magnitude of the association between food security and mercury. Together, these findings suggest that differences in mercury exposure across food security groups are likely related to differences in diet, particularly seafood consumption.

Additional exploratory analyses provided further context for these findings. There was no evidence that associations between food security and metal concentrations differed meaningfully by race or ethnicity, although descriptive differences in exposure were observed across groups. Income stratified analyses suggested that the association between food security and lead may vary across socioeconomic levels, but these results were imprecise and should be interpreted cautiously. Exploratory analyses of early life feeding practices showed limited and inconsistent associations with metal concentrations and were not a central focus of the study.

Taken together, these results indicate that household food security is associated with differences in certain environmental exposures among children, but that these associations vary depending on the metal and its primary exposure pathway. The findings suggest a modest pattern

for lead, no clear association for cadmium, and a more consistent inverse association for mercury that appears to reflect dietary differences.

Metal Interpretations. The patterns observed in this study differentiated meaningfully across metals underscoring that lead, cadmium, and mercury reflect distinct exposure pathways. Interpreting these results requires placing them in the context of how each metal enters the body and how those pathways intersect with social and economic conditions such as food security.

For lead the findings suggest a modest increase in exposure with worsening food security, although these differences were not statistically significant in adjusted models. Children in lower food security households had slightly higher blood lead concentrations with GMRs generally in the range of approximately 1.05 to 1.09 compared to fully food secure households. While confidence intervals included the null, the direction of the association was consistent across models and aligned with descriptive patterns. These findings are consistent with earlier studies showing that less exposure is socially patterned, particularly through housing related risks (Lanphear et al., 2005). Analyses of NHANES data have similarly shown that children from lower income households continue to have higher blood lead levels despite overall declines in population exposure (CDC), 2013). In this context, food insecurity likely reflects broader material and environmental constraints that shape exposure risk. At the same time the relatively small magnitude of differences observed here suggests that disparities in contemporary lead exposure may be more subtle than in the past, and the absence of statistical significance indicates that these findings should be interpreted cautiously.

Results for mercury were more pronounced and consistent. Both total mercury and methyl mercury concentrations were lower among children in households with lower food security, with adjusted reductions of approximately 12 to 20% for those in very low food security

compared to fully food secure households, GMRs = 0.79 to 0.85). This pattern aligns closely with the well-established role of diet as the primary source of mercury exposure. Previous studies using NHANES have shown strong associations between fish consumption and blood mercury levels, with frequent fish consumers having substantially higher concentrations than non-consumers (Cusack et al., 2017). The findings from this study are consistent with this literature and extend it by showing that these dietary patterns vary systematically by food security status.

The dietary analyses conducted here provide additional support for this interpretation. Fish and shellfish consumption was strongly associated with mercury biomarkers, with geometric means exceeding 1.6 for both total and methyl mercury among those reporting fish intake. When dietary variables were included in the models, the association between food security and mercury was weakened, suggesting that differences in seafood consumption explain a substantial portion of the observed relationship. This is consistent with a mediation pathway in which food insecurity influences dietary choices, which in turn shape mercury exposure. These findings also highlight an important nuance, lower mercury levels among food insecure children likely reflect reduced access to seafood rather than reduced environmental exposure. Given that fish consumption is also associated with beneficial nutrients important for neurodevelopment, this pattern does not necessarily indicate a health advantage (Oken et al., 2012).

For cadmium, no clear association with food security was observed. Blood cadmium concentrations remained relatively constant across food security categories, with adjusted estimates consistently close to the null. This finding is broadly consistent with prior literature, which has reported mixed and often weak associations between socioeconomic factors and cadmium exposure (Tellez-Plaza et al., 2012). The absence of a clear pattern in this study likely

reflects the underlying characteristics of cadmium exposure. Unlike mercury, which reflects recent dietary intake, or lead, which is influenced by current environmental conditions, cadmium accumulates in the body overtime, with a long biological half-life (Satarug et al., 2010). As a result, blood cadmium levels may not be strongly influenced by current household conditions such as food security. In addition, cadmium exposure arises from multiple sources, including diet and tobacco smoke, which may dilute observable differences across groups. Although smoking exposure was more common among food insecure households in the sample, adjusting for smoking did not change the results, suggesting that this pathway alone does not account for variation in cadmium levels.

Taken together, these findings both align with and extend prior research. The pattern observed for lead is consistent with longstanding evidence linking exposure to environmental disadvantage, while the mercury findings reinforce the central role of diet in shaping exposure. The lack of association for cadmium is also in line with previous studies suggesting weaker or less consistent socioeconomic patterns. However, this study contributes to the literature by examining these metals simultaneously within a single nationally representative sample and by focusing specifically on food security as a multidimensional measure of social conditions. The use of food security captures both economic constraint and its implications for diet and living conditions, providing a more integrated perspective on exposure pathways.

These results also support a conceptual framework in which food insecurity influences metal exposure through distinct but interconnected mechanisms. For mercury the pathway is primarily diet, reduced access to or consumption of fish and shellfish leads to lower methyl mercury exposure. For lead, the pathway is more closely tied to environmental conditions, with food insecurity serving as an indicator of broader structural disadvantage, including housing

quality. These pathways are not mutually exclusive but reflect different dimensions of how social conditions as well as race/ethnicity shape exposure.

Strengths. This study has several strengths that support the validity and relevance of the findings. This analysis used data from NHANES, which is designed to be nationally representative of the U.S. population. The use of a complex, multistage probability sampling design allows results to be generalized to U.S. children and adolescents when appropriate survey weights are applied. By incorporating survey weights, strata, and primary sampling units into all analyses, this study accounted for the sampling design and produced population representative estimates of exposure. Another strength is the inclusion of multiple metals within a single analytic framework. Many prior studies have focused on a single contaminant, which limits the ability to compare exposure patterns across different pathways. By examining lead, cadmium, total mercury, and methyl mercury simultaneously, this study was able to highlight how different metals are shaped by distinct environmental and dietary mechanisms. The inclusion of both total mercury and methyl mercury as distinct biomarkers provided a more refined assessment of organic mercury exposure and strengthened the interpretation of dietary exposure pathways, particularly those related to fish consumption.

The use of biomarker-based measures of exposure is an important strength. Blood concentrations of metals provide objective, standardized measures that are not subject to recall bias and reflect internal dose rather than self-reported exposure. NHANESS laboratory methods are rigorous, standardized, and subject to extensive quality control procedures. This is especially important when examining low level exposures in population-based studies. Another strength is the analytic approach, which incorporated survey weighted regression models and log transformed outcomes to appropriately model the distribution of metal concentrations. Reporting

results as GMRs allows for interpretation of relative terms, which is more appropriate for right skewed biomarker data. In addition, this study included sensitivity analyses to examine the robustness of findings. This study extends prior work by specifically utilizing food security as a multidimensional social determinant of exposure and by exploring potential mechanisms. Through including variables such as fish intake and household smoking, that are known exposure pathways, this study moves past simple associations and accounts for a more nuanced understanding of how social and behavior factors shape exposures.

Limitations. Several limitations should be considered when interpreting the findings of this study. First, the cross-sectional design of NHANES limits the ability to draw causal inferences. Since exposure and outcome are measured at the same point in time, it is not possible to determine the temporal sequence between food security and metal exposure. As a result, the associations observed in this study should be interpreted as descriptive rather than causal. Second, food security was measured at the household level using self-reported survey data. While the USDA food security module is widely validated and commonly used, it captures conditions at the household level rather than individual experiences which may vary within households. In addition, food security reflects conditions over the past 12 months, whereas biomarker measures may reflect more recent or cumulative exposures depending on the metal. This mismatch in time scale may reduce observed associations.

Residual confounding is also a concern. Although the models adjusted for key demographic and socioeconomic variables, including age, sex, race/ethnicity, and income to poverty ratio, other factors that influence exposure may not have been fully captured. For example, housing characteristics, detailed dietary intake, and neighborhood condition were not fully accounted for in the main models. While some of these factors were explored in sensitivity

analyses, unmeasured or imprecisely measured confounders may still influence the results. Measurement limitations related to the biomarkers themselves should also be considered. Blood concentrations reflect different exposure windows depending on the metal. For instance, blood mercury primarily reflects recent dietary intake, whereas cadmium reflects longer term cumulative exposure (Satarug et al., 2010). The difference complicates direct comparisons across metals and may partly explain why associations vary by outcome. In addition, some biomarkers, particularly mercury species, had a substantial proportion of values below the limit of detection, which can reduce statistical power and precision.

While NHANES provides nationally representative data, certain subgroups may still have limited sample sizes, particularly in stratified or exploratory analyses. This may result in wider confidence intervals and reduced ability to detect statistically significant differences. As a result, some findings, particularly those from subgroups or exploratory analyses should be interpreted with caution.

Despite these limitations, this study provides insight into how food security relates to environmental exposures in children. These findings should be viewed as contributing to a broader work of evidence and as a foundation for future research.

CONCLUSION

This study examined the relationship between household food security and exposure to toxic metals among U.S. children and adolescents, using nationally representative NHANES data. The findings indicate that food insecurity is associated with metal exposure in ways that differentiate by contaminant. This reflects distinct underlying pathways. A modest, non-significant increase in blood lead concentrations was observed among children in lower food security households, consistent with environmental exposure patterns tied to housing and

neighborhood conditions. Mercury concentrations both total and methyl mercury were significantly lower among children experiencing lower food security, with reductions of about 15 to 20% in adjusted models. Cadmium showed no clear association, with relatively stable levels across food security categories. These results together suggest that food insecurity is not uniformly associated with higher or lower exposure but instead related to different metals through different patterns.

A key implication of these findings is the importance of distinguishing between environmental and dietary pathways of exposure. For mercury, the results strongly support a dietary mechanism, in which lower seafood consumption among food insecure households leads to lower mercury exposure. This interpretation is reinforced by the pronounced association between fish intake and mercury biomarkers observed in the analysis. For lead, the pattern is more consistent with environmental pathways, where food insecurity reflects broader structural disadvantages like housing quality that can increase exposure risk. These pathways are not mutually exclusive but highlight how social conditions shape exposure through multiple interconnected ways.

These findings have important implications for public health. Efforts to address food insecurity are often focused on improving access to adequate and nutritious food but the results of this study suggest that such interventions may also influence patterns of environmental exposure. For instance, increasing access to a wider range of foods, like seafood, has both nutritional benefits and implications for mercury exposure. At the same time, addressing food insecurity alone is unlikely to eliminate disparities in exposures such as lead where they are more directly tied to environmental conditions. This highlights the need for integrated approaches that consider nutritional and environmental health. Overall, this study highlights the value of using

food security as a lens for understanding how social and economic conditions shape environmental exposures in children and adolescents. By examining multiple metals within a single framework, it provides a more comprehensive view of exposure pathways and underscores the importance of considering both diet and environment in efforts to reduce health disparities. Future research that builds on these findings can utilize longitudinal designs to further clarify these relationships and to inform interventions.

APPENDICES

Appendix A: Appendix Tables

Appendix Table A. Mechanism and Exploratory Effect-Modification Analyses

Appendix Table B. Missingness of Variables Used in Analysis

Appendix Table C. Limits of Detection Summary

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Appendix B: Appendix Figure

Appendix Figure A. Adult Household Food Security Distribution by Race/Ethnicity

APPENDIX A

Appendix Table A. Mechanism and Exploratory Effect-Modification Analyses

Outcome	Result	Estimate or test	p-value	Unweighted n
Mercury diet sensitivity				
Total mercury	Food security: Marginal vs Full	0.90 (0.82, 0.98)	0.020	4253
Total mercury	Food security: Low vs Full	1.00 (0.90, 1.11)	0.997	4253
Total mercury	Food security: Very low vs Full	0.91 (0.81, 1.02)	0.100	4253
Total mercury	Fish intake, yes vs no	1.67 (1.54, 1.81)	<0.001	4253
Total mercury	Shellfish intake, yes vs no	1.31 (1.21, 1.42)	<0.001	4253
Methyl mercury	Food security: Marginal vs Full	0.92 (0.85, 1.00)	0.054	4209
Methyl mercury	Food security: Low vs Full	1.01 (0.93, 1.10)	0.800	4209
Methyl mercury	Food security: Very low vs Full	0.93 (0.85, 1.03)	0.146	4209
Methyl mercury	Fish intake, yes vs no	1.58 (1.48, 1.69)	<0.001	4209
Methyl mercury	Shellfish intake, yes vs no	1.25 (1.17, 1.34)	<0.001	4209
Food insecurity × race interaction				
Total mercury	Global interaction test	Global p-value	0.820	5171
Methyl mercury	Global interaction test	Global p-value	0.685	5116
Blood lead	Global interaction test	Global p-value	0.795	4289
Blood cadmium	Global interaction test	Global p-value	0.973	5171
Lead by income stratum				
Blood lead	Food insecure vs secure, PIR <1.0	1.11 (1.00, 1.23)	0.047	1240
Blood lead	Food insecure vs secure, PIR 1.0-<2.0	0.95 (0.86, 1.06)	0.370	1128
Blood lead	Food insecure vs secure, PIR >=2.0	1.15 (1.01, 1.30)	0.033	1921
Lead × income interaction				
Blood lead	Global interaction test	Global p-value	0.076	4289

Appendix Table B. Missingness of Variables Used in Analysis

Variable	Total n	Missing, n (%)
Blood lead	9689	4861 (50.2%)
Blood cadmium	9689	3866 (39.9%)
Total mercury	9689	3866 (39.9%)
Methyl mercury	9689	3929 (40.6%)
Inorganic mercury	9689	3929 (40.6%)
Food security (FS4)	9689	873 (9.0%)
Food security (binary)	9689	873 (9.0%)
Race/ethnicity	9689	0 (0.0%)
Sex	9689	0 (0.0%)
Age group	9689	0 (0.0%)
PIR (continuous)	9689	1429 (14.7%)
PIR (category)	9689	1429 (14.7%)
Household smoking	9689	863 (8.9%)
Fish intake	9689	3356 (34.6%)
Shellfish intake	9689	3352 (34.6%)
Breastfeeding category	9689	6406 (66.1%)
Formula timing	9689	6434 (66.4%)

Appendix Table C. Limits of Detection Summary

Outcome	With LOD indicator	Below LOD, n (%)
Pb	4828	3 (0.1%)
Cd	5823	2163 (37.1%)
THg	5823	3106 (53.3%)
MeHg	5760	3931 (68.2%)
Inorganic Hg	5760	5398 (93.7%)
Ethyl Hg	5760	5735 (99.6%)

Note: NHANES analytic result variables already include LLOD/sqrt(2) substituted values for results below the limit of detection.

Appendix Table D. Adjusted Associations Between Household Food Security and Blood Metal Concentrations (Final Sequential Model)

Outcome	Comparison	GMR (95% CI)
Blood lead	Marginal vs Full	1.05 (0.98, 1.11)
Blood lead	Low vs Full	1.08 (0.98, 1.20)
Blood lead	Very low vs Full	1.05 (0.97, 1.14)
Blood cadmium	Marginal vs Full	0.97 (0.91, 1.04)
Blood cadmium	Low vs Full	1.04 (0.97, 1.13)
Blood cadmium	Very low vs Full	1.01 (0.94, 1.07)
Total mercury	Marginal vs Full	0.91 (0.83, 1.00)
Total mercury	Low vs Full	0.97 (0.87, 1.09)
Total mercury	Very low vs Full	0.86 (0.78, 0.95)
Methyl mercury	Marginal vs Full	0.92 (0.84, 1.01)
Methyl mercury	Low vs Full	0.99 (0.90, 1.09)
Methyl mercury	Very low vs Full	0.90 (0.83, 0.97)

Note. Survey-weighted log-linear regression models estimating associations between household food security and blood metal concentrations. Models adjusted for age group, sex, race/ethnicity, poverty-income ratio, and survey period. Values are geometric mean ratios (GMR) with 95% confidence intervals.

Appendix Table E. Binary Food Insecurity Sensitivity Models

Outcome	Comparison	Unweighted n	GMR (95% CI)	p-value
Blood lead	Food insecure vs food secure	4289	1.06 (0.99, 1.12)	0.072
Blood cadmium	Food insecure vs food secure	5171	1.03 (0.98, 1.09)	0.198
Total mercury	Food insecure vs food secure	5171	0.95 (0.88, 1.03)	0.185
Methyl mercury	Food insecure vs food secure	5116	0.97 (0.91, 1.04)	0.377

Appendix Table F. Cadmium Model Additionally Adjusted for Household Smoking

Outcome	Contrast	Unweighted n	GMR (95% CI)	p-value
Blood cadmium	Food security: Marginal vs Full	5169	0.97 (0.91, 1.03)	0.324
Blood cadmium	Food security: Low vs Full	5169	1.04 (0.96, 1.12)	0.346
Blood cadmium	Food security: Very low vs Full	5169	1.00 (0.93, 1.06)	0.918
Blood cadmium	Any household smoker vs none	5169	1.05 (1.00, 1.09)	0.030

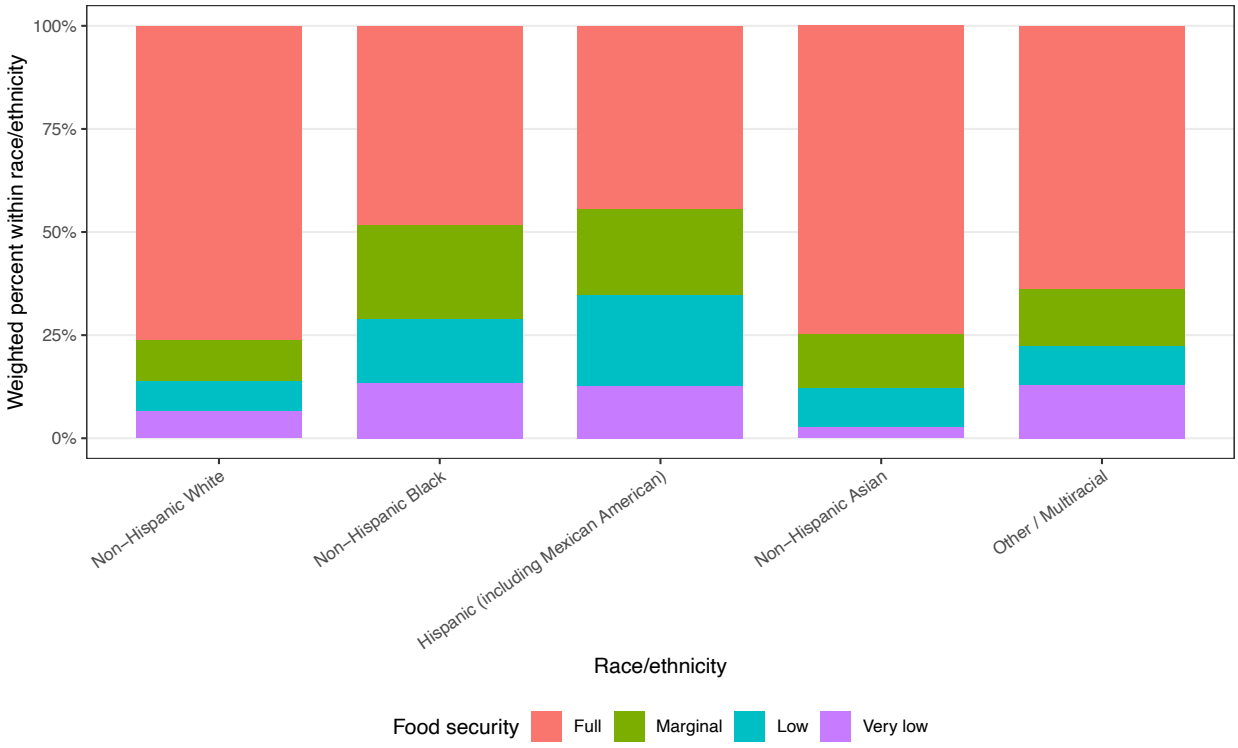
Appendix Table G. Breastfeeding and Formula Timing Exploratory Models

Contrast	Outcome	Unweighted n	GMR (95% CI)	p-value
Breastfeeding duration				
Short (1-30 d)	Blood lead	475	1.04 (0.78, 1.41)	0.765
Medium (31-180 d)	Blood lead	475	0.90 (0.75, 1.08)	0.231
Long/ongoing (>180 d)	Blood lead	475	0.98 (0.84, 1.14)	0.779
Short (1-30 d)	Blood cadmium	1350	1.07 (0.93, 1.22)	0.325
Medium (31-180 d)	Blood cadmium	1350	1.06 (0.97, 1.17)	0.191
Long/ongoing (>180 d)	Blood cadmium	1350	1.13 (1.04, 1.22)	0.006
Short (1-30 d)	Total mercury	1350	1.03 (0.84, 1.26)	0.781
Medium (31-180 d)	Total mercury	1350	0.98 (0.82, 1.17)	0.843
Long/ongoing (>180 d)	Total mercury	1350	1.07 (0.93, 1.23)	0.348
Short (1-30 d)	Methyl mercury	1303	1.06 (0.90, 1.24)	0.460
Medium (31-180 d)	Methyl mercury	1303	1.03 (0.90, 1.18)	0.615
Long/ongoing (>180 d)	Methyl mercury	1303	1.06 (0.95, 1.17)	0.284
Formula timing				
Early formula ≤30 d	Blood lead	466	0.76 (0.59, 0.98)	0.035
Later formula 31-365 d	Blood lead	466	0.85 (0.68, 1.06)	0.139
Early formula ≤30 d	Blood cadmium	1332	0.88 (0.80, 0.96)	0.005
Later formula 31-365 d	Blood cadmium	1332	0.93 (0.86, 1.01)	0.082
Early formula ≤30 d	Total mercury	1332	1.06 (0.86, 1.30)	0.573
Later formula 31-365 d	Total mercury	1332	1.00 (0.82, 1.23)	0.992
Early formula ≤30 d	Methyl mercury	1285	0.98 (0.81, 1.19)	0.851
Later formula 31-365 d	Methyl mercury	1285	0.98 (0.80, 1.19)	0.807

Note: Breastfeeding models adjusted for age, sex, PIR, race/ethnicity, and survey period. Formula models additionally adjust for breastfeeding category. Results are exploratory.

APPENDIX B

Appendix Figure A. Adult Household Food Security Distribution by Race/Ethnicity



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