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Review Article

Gender-Specific chemical exposure in arctic communities

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Abstract

This review explores the challenges Arctic populations face regarding contaminant exposure and its intricate relationship with traditional diets. Particular attention is given to the unique situation of northern women, whose dietary habits influence their exposure to these contaminants. Despite the recent and rapid dietary shift towards a more "westernized" diet, traditional foods remain a cornerstone of Arctic communities' sustenance. However, the consumption of such foods, particularly marine mammals, has been consistently associated to elevated levels of lipophilic contaminants including persistent organic pollutants (POPs) and trace elements. Notable gendered differences emerge in dietary patterns, with northern women reportedly consuming fewer traditional products, thereby reducing their contaminant exposure. Additionally, women of childbearing age benefit from unique elimination pathways—through pregnancy, breastfeeding, and menstruation—that men lack. This combination of lower traditional food intake and the existence of gender-specific elimination routes has resulted in a lower contaminant burden in women compared to men. For instance, blood concentrations of organic contaminants such as polychlorinated biphenyls, organochlorine pesticides, per- and polyfluoroalkyl substances, and trace elements like lead, are on average 20 to 40% lower in women. Nevertheless, these lower contaminant levels do not necessarily imply reduced health risks, as women's susceptibility to these substances may differ markedly from that of men.

Key words: Arctic dilemma; organochlorine pesticides (OCPs); polychlorinated biphenyls (PCBs); PFAS; sex-specific; bioaccumulation; dietary exposure.

Introduction

There are three major human exposure routes for contaminants, namely (a) inhalation of contaminants in air, vapor, or aerosols, including tobacco sources; (b) dermal contact with contaminated media, such as water, soil, dust, materials, or personal care products; and (c) ingestion of pollutants present in food and drinks. Whereas the environmental burden of contaminants in the Arctic regions is lower than in other areas worldwide,[1] biomonitoring studies in these populations have revealed remarkably high levels of certain contaminants in blood and urine samples.[2-6] Numerous investigations aimed at determining the nature, origin, and concentrations of these contaminants have been conducted in past years, most of them focusing on diet as the main exposure route.[7-11]

Upon entering the organism, contaminants may be either metabolized and excreted, or accumulated in various tissues, including fat. Their biological fate depends to a great extent on their physicochemical properties: lipophilic compounds such as persistent organic pollutants (POPs) are more prone to prevail in animal tissues, resulting in a bioaccumulation process. These compounds are also susceptible to biomagnification through the food chain and can reach significantly high levels in predator species such as whale or shark.[12,13] This phenomenon is of particular relevance for Arctic communities, whose traditional diet relies on the consumption of top predators and other animals occupying high trophic levels. Despite the decrease in the consumption of wild-harvested traditional foods (including sea mammals, fish, terrestrial animals, birds, berries and plants), often referred to as "country food", populations in the Arctic remain significantly more exposed to chemical contaminants compared to other communities with a different diet.[14] This increased exposure may result in human health issues, particularly for vulnerable groups: for instance, in a recent study, marine food consumption was linked to the activation of the aryl

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hydrocarbon receptor (high AhR-TEQ levels) in pregnant women, with implications for the fetal growth.[15] Despite these risks, traditional food continues to play a crucial role in the culture, identity, and traditions of Arctic communities, and it is essential for local food security, providing important nutrients and minerals that are not readily available through other dietary sources.[16,17]

The objective of this review is to critically assess the contaminant exposure of Arctic communities through their traditional diet, with a particular focus on women and men as separated population groups. This analysis will evaluate their exposure to contaminants—including potential differences in absorption, distribution, metabolism, and excretion (ADME) processes between genders, compare their dietary patterns, and evaluate the attention they have received in scientific research and awareness campaigns about contaminant risks in food. Within a broader context, this review aims to contribute to decades of research documenting the impacts of contaminants on the Arctic environment and peoples.[18,19] Findings from Arctic contaminant research have played a crucial role in shaping international agreements, like the Stockholm Convention, and the Arctic's unique context demands (from both the scientific community and policy-makers[20]) for a gender-based analysis of the health effects of various pollutants in the region.[21]

Methodology

The present work was based on a thorough literature review using the Scopus database and including research works published within the past 25 years (2000–2024) in specialized journals. The search strategy was designed to encompass a broad spectrum of research by employing multiple search queries tailored to the scope of our review. The key terms used included combinations of "diet", "traditional food", "TF", "country food", "market food", "food safety", "arctic", "women", "men", "female", "male", "population", "exposure", "biomonitoring", "contaminants", etc., along with specific Boolean operators to refine the search results. Particular attention was paid to studies reporting sex-specific or gender-specific differences in exposure levels, dietary patterns, or biomonitoring results, as the review aimed to explore how chemical exposure in Arctic communities may vary across genders. In addition to the database search, reference lists of all articles identified through the initial Scopus search were manually examined. This supplemental hand-searching was intended to capture additional significant studies that may not have appeared in the database search but were cited by the reviewed studies. Our approach for defining the scope of Arctic regions in this review was based on the inclusion of articles where "Arctic" was specified in the title, abstract, or keywords. This criterion aimed to reflect a broad and non-specific geographical selection without actively targeting particular regions. As a result, studies from Iceland were absent in our dataset: although Iceland is recognized as an Arctic state by the Arctic Council, it does not appear under the "Arctic" keyword in most scientific literature.

The literature review has been limited to peer-reviewed scientific articles published in academic journals and dealing with (i) the biomonitoring of contaminants in human samples from Arctic populations, and/or (ii) the dietary habits of these populations and the role of traditional food in the current societies. Although technical reports from organizations such as the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) were excluded, some of the studies reviewed relied partly or entirely on data from these reports.

A total of 81 research works describing the human biomonitoring of environmental contaminants in Arctic populations, published over the last 25 years (2000–2024), have been analyzed within the present review. The communities and regions that have received the most attention were located in Canada (with up to 32 studies focusing on this region), Greenland (25 studies, sometimes combined with other regions), and Russia (nine studies); additionally, six studies were conducted in Norway, five in Alaska (USA), two in Finland, and two across a combination of these Arctic regions.

This review also includes studies reporting the dietary habits of the Arctic populations, the multiple roles of traditional food in the Arctic culture and food security, and the link between traditional food consumption and contaminant exposure.

Sex-specific models of contaminant bioaccumulation in human arctic populations

The vast majority of the biomonitoring studies (68 out of 81 works) report the analysis of contaminants in blood samples, while the analysis of urine, hair, or breast milk is described in only eight, seven, and three works, respectively. Some of these studies collected and analyzed several of these matrices, which were sometimes combined with other types of data such as anthropometric measurements,[10,15,22] levels of essential elements such as manganese or zinc,[23] assessment of menstrual disturbances,[24] child behavior,[25] or bone health.[26] Notably, a total of five studies combined the biomonitoring of human samples with the analysis of food samples to evaluate potential links between diet and contaminant exposure.[3,8,27,28]

As regards the analytical scope of these studies, lipophilic POPs, including polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs), polybrominated diphenyl ethers (PBDEs), etc., constitute the most widely analyzed group of compounds (63% of the studies), followed by trace elements (47%) and per-, or polyfluorinated substances (PFAS, 26%). Most of these contaminant families (with the exception of trace elements) contain congeners included in the Stockholm convention. Although the vast majority of biomonitoring studies focus on one or more of the mentioned chemical groups, some authors analyzed other types of environmental contaminants (bisphenols, parabens, phthalates, alternative plasticizers),[29] or health biomarkers and nutrients such as fatty acids,[30-32] selenoneine,[33] or docosahexaenoic acid.[34]

As shown in Figure 1A, up to 35 studies reported the biomonitoring of these substances in the general population, while a significant number of works specifically targeted pregnant women (17 studies), women in general (10 studies), or mother-child pairs (eight studies). In contrast, only a limited number of studies examined other population groups, such as men (five studies), male-female couples (two studies), or children (four studies). Interestingly, in some of the cases where men were the main focus, women were often included indirectly in the study design. Varakina et al. presented separate publications for men and women from the same Russian Arctic areas,[35,36] while Lenters et al. studied male partners of pregnant women.[37] This highlights the prominent role of the gender dimension in Arctic biomonitoring studies, with particular attention given to the vulnerabilities of women in these communities. This includes the context of maternal transfer of contaminants during pregnancy and lactation, which represent critical exposure windows for the developing child. Although this focus is scientifically justified, it has

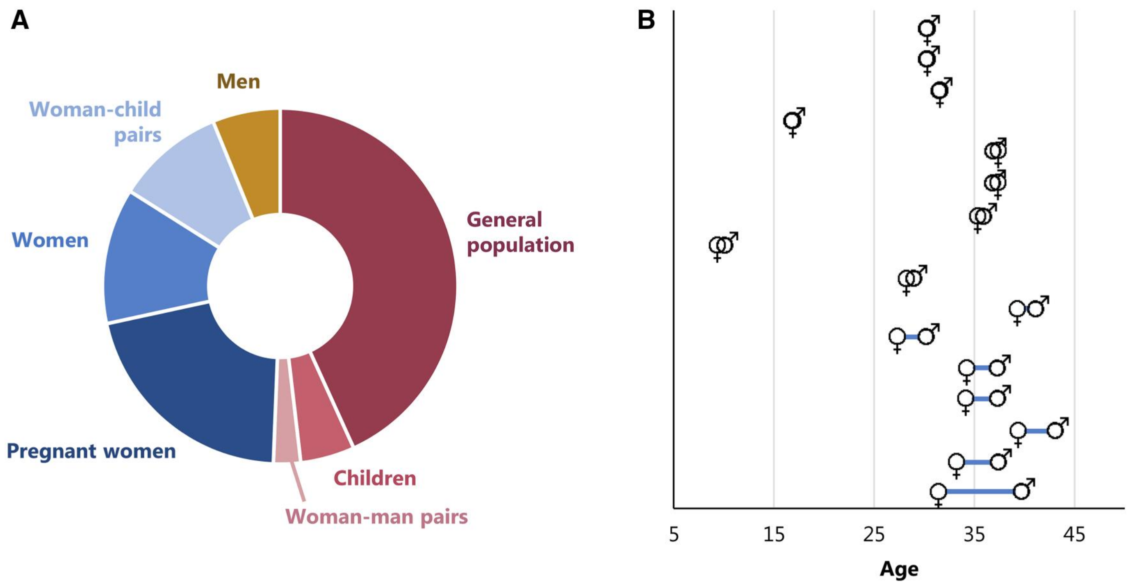

Figure 1. (**A**) Demographics of 81 research studies describing the human biomonitoring of environmental contaminants in Arctic populations, published over the last 25 years (2000–2024); (**B**) median age of male and female participants in studies reporting contaminant levels separately by sex.

inadvertently led to an underrepresentation of men as a distinct study population. Evaluating whether this trend can be extended to other non-Arctic communities is beyond the scope of the present review, although it appears unlikely because the majority of biomonitoring studies worldwide focus on working populations, which have historically included a higher proportion of men than women.[38]

General patterns and main causes of gender-specific organic contaminant levels

In order to explore potential gender-based differences in internal contaminant levels, a comparative analysis was conducted using data from 30 studies that reported separately the results for men and women. Within each study, the summed concentrations of all compounds in each chemical family considered—ie, PCBs, OCPs, PFAS, and trace elements—were compared between both sexes, and the relative differences in these concentrations were calculated. Due to the limited number of independent data regarding the analysis of PBDEs and PCDD/Fs, reported by four and two works, respectively, these chemical families were excluded from the evaluation. Given the potential for bioaccumulation of the chemical contaminants studied, their levels in human tissues are expected—and have been consistently proved—[39,40] to increase with age. Thus, ensuring comparable participant ages between men and women is crucial to avoid confounding variables other than gender. Most studies met this requirement and provided statistical data about the participants' ages (Figure 1B).[41-43] The median age difference between male and female participants in the vast majority of studies was lower than 4 years, with only two exceptions (4.3 and 8.5 years' difference). Data from the latter work were treated with particular caution during the subsequent analysis. It is also essential to consider the year of birth of participants, as individuals born in different decades may have been exposed to varying environmental contaminant levels during critical periods of their lives. In this sense, our analysis strictly compares gender-specific data within each study, thereby ensuring that comparisons across different years do not confound our results.

The results are summarized in Figure 2A–C, which illustrates the normalized differences observed for the chemical families analyzed in at least 10 independent research studies and/or matrices (represented by individual bars). Due to the limited number of independent data regarding the analysis of PBDEs and PCDD/Fs, reported by four and two works, respectively, these chemical families were excluded from the evaluation. The left part of the graph corresponds to studies in which the total concentration of the contaminant family was higher in men (negative ratio women/men), while the studies reporting higher levels in women are depicted on the right side of the graph. As can be seen, the vast majority of studies report lower PCB, OCP, and PFAS concentrations in women compared to men. Although these gender-based differences are generally small, representing 20–40% lower concentrations in women compared to men, this systematic finding in virtually all works is noteworthy. For example, among the 12 studies that analyzed PCBs in both males and females, PCB levels were 10–55% lower in the latter, with no study reporting comparable levels between sexes or a higher concentration in women. Similar patterns can be observed for OCPs and PFAS. This consistent trend suggests that men are generally exposed to or retain higher levels of most chemical contaminant families. Additionally, although outside of the scope of the present review, biomonitoring studies from non-Arctic populations also exhibit this pattern for a wide variety of chemical contaminant families, as observed, for instance, in multiple EU-based studies from the European Human Biomonitoring Initiative (HBM4EU) database.[44]

The differences between males and females can in general be attributed to sex-specific processes that reduce contaminant levels in women, such as menstruation, as well as the transfer of contaminants during pregnancy and breastfeeding.[45] It is noteworthy that, while the latter processes lower the maternal body burden, they imply a transmission of contaminants to the fetus or infant, raising concerns about early-life exposure and associated health risks. These were the most commonly cited causes in the reviewed studies, focused exclusively on Arctic communities. However, these processes are also applicable to individuals in populations worldwide, and hence they are relevant contaminant excretion pathways beyond the Arctic context.[46]

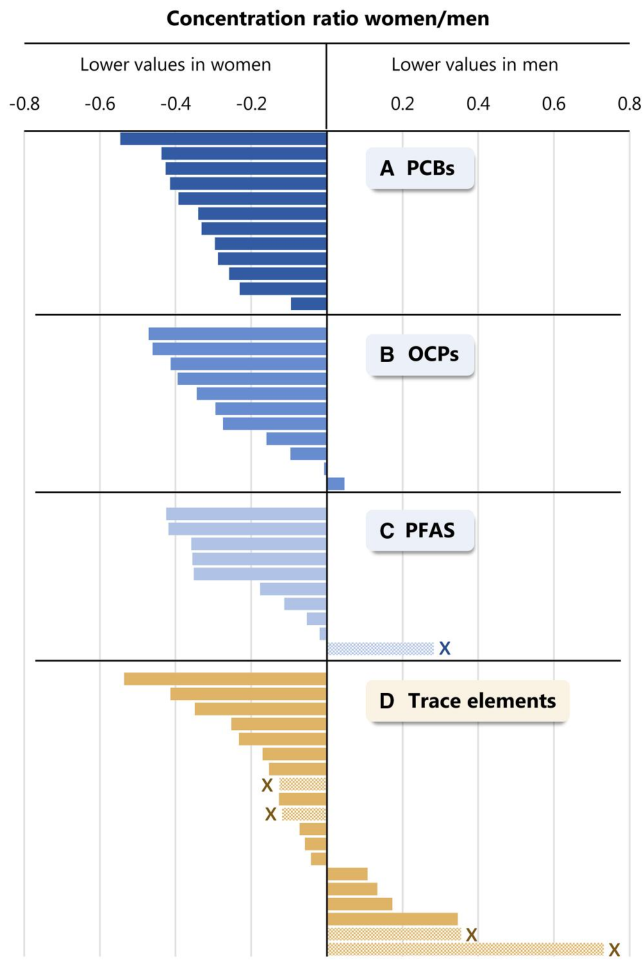

Figure 2. Concentration ratios in biological samples from women relative to men, based on data extracted from 30 studies, for (**A**) sum PCBs, (**B**) sum OCPs, (**C**) sum PFAS, (**D**) sum trace elements (Pb, Cd, Hg, As). Each bar represents a single study's findings, where negative values (left) indicate lower concentrations in women compared to men, and positive values (right) indicate higher concentrations in women. Bars marked with an X represent data from hair or urine samples, while unmarked bars correspond to blood samples. Additional details can be found in Table S1.

Berg et al. observed significantly lower PFAS levels in multiparous women from Tromsø (Northern Norway) compared to those who had never given birth,[47] and a similar pattern was reported by Jönsson et al. for PCBs and OCPs.[48] Similarly, in a different study, the contaminant load in blood samples from men and nulliparous women was found to be similar, while the concentration in parous women was significantly lower.[49] For their part, Chateau et al. reported stronger gender-based differences for younger women compared to those over 44 years of age.[43] Hence, women of childbearing age (including pregnant, non-pregnant and breastfeeding women) tend to exhibit faster contaminant clearance rates due to these elimination pathways, as has also been described by other authors.[31,40,50,51] In a study by Sandanger et al. the POP burden was not correlated to age for women under 40 years old, but there was a significant increase in these levels with age for older women,[52] probably due to the onset of menopause and the absence of further pregnancies, which reduce the extent of these elimination pathways. Nøst et al. hypothesized that the lower concentrations in women compared to men may be partly due to the presence of mothers in their study population,[49] which can be applied to other studies considering the maternity rates in adult women.

The physicochemical properties of the different contaminant families play a major role in their metabolism and excretion routes: PFAS, with amphiphilic properties, exhibit distinct behaviors in the body compared to lipophilic contaminants like PCBs or OCPs. The former tend to accumulate at protein interfaces, differentiating them from other persistent organic pollutants that are primarily stored in fatty matrices and are prone to bioaccumulation in human tissues over time.[53] As a result, although lower levels of all organic contaminants were observed in women, the mechanisms driving these differences in one chemical family may not necessarily apply to others. In some cases, even the compounds within one chemical family may behave differently, in particular when congeners exhibit different physicochemical properties. This is particularly evident in the case of PFAS, where chain length—and consequently polarity—directly influences their behavior: studies have shown that gender-based differences are more pronounced for short-chain PFAS such as PFHxS, which suggests that these elimination routes are more pronounced for the most polar congeners analyzed, those with shorter carbon chains.[47,54]

Additional biological factors, such as differences in renal clearance of metabolized compounds—ie, higher excretion of PFAS via the kidney in women—and the influence of sex hormones on excretion rates further contribute to this disparity and result in higher PFAS levels detected in urine samples from females.[31,50] This is also the reason for the only exception to the gender-based pattern in PFAS: Long et al. who analyzed PFAS in urine samples, found total PFAS concentrations to be 28% higher in women's urine compared to men's.[31] However, when this study analyzed PFAS in blood samples from the same participants, the results aligned with the general trend observed across other studies, showing 36% lower concentrations in women compared to men. Some of these elimination routes, as discussed previously, are strongly dependent on the physicochemical properties of the contaminants and might not be applicable to lipophilic contaminants, which are not easily metabolized.

In addition, lifestyle factors related to the traditional gender roles may influence the different exposure of men and women: in a study in 2017 by Byrne et al. the concentrations of some PBDEs in home dust samples were significantly associated with their levels in blood from women (who have traditionally spent more time indoors) but not from men,[28] while a different biomonitoring study attributed the higher levels of plasticizers in women to their greater use of personal care products.[29] However, the most relevant contaminant exposure route for Arctic populations is related to diet, which is important for both men and women, but affects them differently due to sex-specific dietary habits—a topic that will be explored in more detail in a dedicated section hereafter.

Despite the lower contaminant levels generally detected in women, the biological effects caused by these substances may differ between sexes. For instance, PFOS has only been negatively associated with tryacylglycerols (linked to energy storage and cholesterol) in women,[43] while some PFAS show distinct effects on thyroid hormones according to sex—ie, negative associations in men and positive associations in women.[41] These differences suggest that women and men may process or respond to chemical contaminant exposure in unique ways, potentially due to variations in hormonal regulation or metabolic pathways influenced by sex.

Patterns and disparities in trace element accumulation

While women generally exhibit lower levels of trace elements than men, this trend is less consistent than for organic contaminants, with six out of nineteen studies reporting higher concentrations in women (Figure 2D). A closer examination of the individual compounds reveals varying accumulation behaviors for the most commonly detected compounds (Figure 3). Lead mirrors the pattern observed for organic contaminants, with lower concentrations in women compared to men in all 10 studies that analyzed this element. Conversely, no clear tendency could be observed for cadmium or mercury: approximately half of the studies reported higher concentrations in men, while the other half found these elements to be more abundant in women. The contribution of these elements, particularly mercury, is responsible for the overall higher levels in women reported by several studies. The primary causes of trace element exposure in Arctic populations are smoking, particularly for cadmium,[5,55] and the consumption of marine traditional foods, in the case of mercury and other trace elements.[3,4,56] However, the reasons behind the consistent lower levels of lead in women are not explicitly addressed in the reviewed literature.

Dietary drivers of gender differences in contaminant levels

The arctic dilemma: traditional arctic diet and contaminant burden

Arctic populations have a distinctive traditional diet, mainly consisting of wild-harvested foods, including marine and land animals, fish, birds, eggs, as well as various wild berries. Among 40 recent studies reporting a list of traditional food items commonly consumed by Arctic populations, seal and caribou are mentioned as relevant food items in at least 80%, followed by Arctic char, whales such as beluga, narwal or bowhead (primarily their skin and blubber, known as "muktuk" or "mattak"), trout, and polar bear (Figure 4). Among these products, seafood is a known major source of POPs,[25,37,52,57] trace elements,[56] and chemical contaminants in general.[8,22,27,31,58,59] Beluga whale, a highly valued delicacy that plays a key role in Inuit diet and culture, can bioaccumulate such a high burden of pollutants that it has been identified as the main contributor to human exposure to certain contaminant families.[3,6] Similarly, the consumption of polar bear has been linked to elevated levels of POPs in human blood,[10] while caribou is one of the main contributors to HCB exposure.[60] For their part, the high levels of PCBs, PFAS, and other POPs in wild birds and their eggs have led to recommendations to limit or avoid their consumption.[61,62]

The high prevalence and levels of chemical contaminants in traditional foods, combined with the role of this diet in food adequacy, identity, and culture, has resulted in the so-called "Arctic dilemma": the difficulty in balancing the social, cultural, and nutritional benefits of traditional food items with the toxicological risks of the contaminants they may contain.[63] Traditional food items are among the main contributors to proteins and other micronutrients—eg, iron, vitamins, phosphorous, and thus reach higher Healthy Eating Index scores than non-nutrient-rich, imported food products that are often high in carbohydrates and fats.[64-73] The perceived benefits of traditional food products were also highlighted in a recent survey by Nyholm et al. where 42% of respondents in Alaska reported that health problems were caused or exacerbated by a lack of traditional foods and only 9% saw no link.[74] These "country foods" are central to Arctic culture and are recognized as the most important markers for Inuit identity and sense of community.[16,75-77] In a survey by Lambden et al. women in 44 Canadian Arctic communities reported a relationship between traditional food consumption and health, well-being, connection to nature, culture, respect, pride, and confidence, among others.[17] Beyond the food itself, the practices of hunting, gathering, harvesting, processing, sharing, and eating country food are key cultural and spiritual acts, and are essential for fostering a sense of place, strengthening connections to the land and waters, preserving language, and upholding Inuit food sovereignty, food security, health, and well-being.[78]

Despite the general perception that traditional food is healthier than imported store-bought food,[79,80] Arctic populations are increasingly aware of the potential presence of contaminants in these items. In a recent survey conducted in the Dehcho and Sahtú Regions of the Northwest Territories in Canada, 60% of participants expressed concerns about the safety and quality of traditional foods.[81] These items were also identified as the primary self-perceived sources of contaminant exposure.[82] However, there is no clear pattern in how awareness of contaminants varies by gender: one study reported that women were

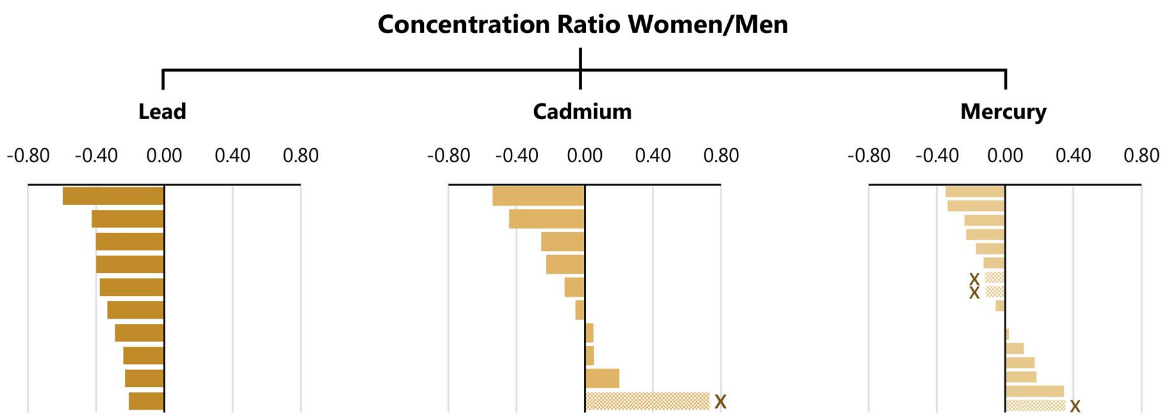

Figure 3. Trace element concentration ratios in biological samples from women relative to men, based on data extracted from 16 studies. Arsenic was not included in the present evaluation due to the low number of studies that report its levels in men and women. Each bar represents a single study's findings, where negative values (left) indicate lower concentrations in women compared to men, and positive values (right) indicate higher concentrations in women. Bars marked with an X represent data from hair or urine samples, while unmarked bars correspond to blood samples. Additional details can be found in Table S2.

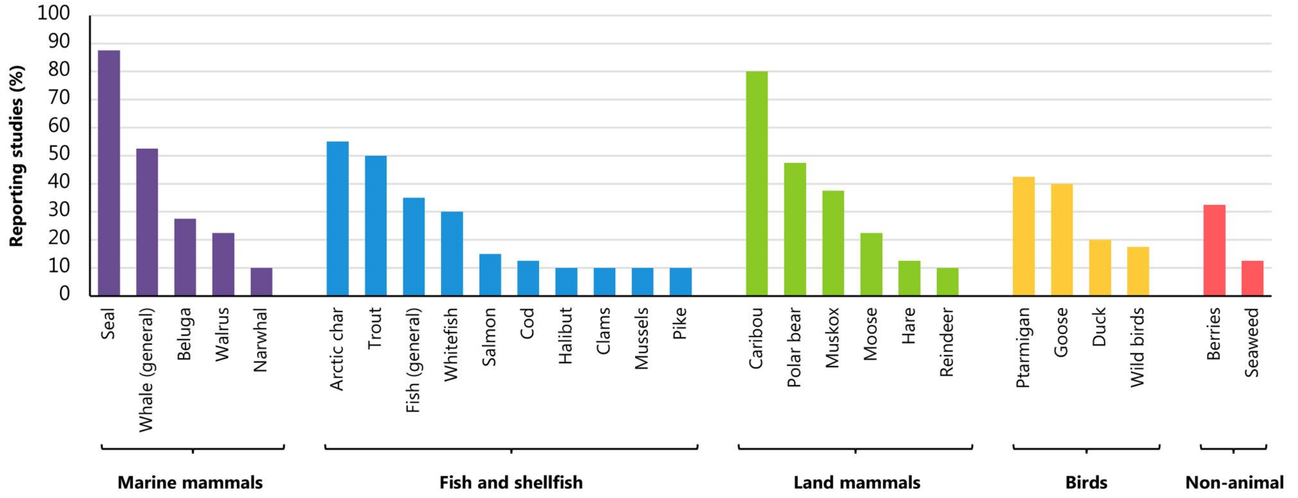

Figure 4. Frequency of traditional Arctic food items mentioned in at least four (10%) out of 40 dietary studies (2004–2024), arranged by food category.

more aware of the presence of contaminants in food, while another found the opposite, suggesting that these messages may reach men and women differently depending on the context.[81,82] Awareness of these potential toxicological risks has led the scientific and international community to issue recommendations to limit, avoid, or not to increase the consumption of certain traditional food products, targeting the general population or vulnerable groups such as women or children.[32,39,61,83] It has also prompted authorities to implement programs aimed at replacing highly contaminated foods with alternatives that have similar nutritional value but lower contaminant levels, such as the Arctic Char Distribution Project, which was targeted exclusively at pregnant women.[84]

However, it is generally accepted that the cultural, social, and nutritional and well-being benefits of consuming traditional foods outweigh the risk of contaminant exposure for Arctic populations.[27,60,85,86] This situation illustrates the challenges Arctic communities face in reconciling the traditional diet with contemporary health concerns: the core of the Arctic dilemma and the main source of contaminant exposure.

Arctic dietary transition for men and women

Although most participants in surveys, questionnaires, and interviews state that they prefer a traditional diet over imported store-bought food products,[74,79,87,88] Arctic communities have been undergoing a drastic nutritional transition towards a more "westernized" diet over the last decades.[89] This change has led to a reduced consumption of traditional food items, which has positively impacted the contaminant burden in human tissues. In fact, most recent biomonitoring studies have reported lower levels of POPs and trace elements in blood samples from Arctic populations compared to previous works.[2] However, this transition does not necessarily lead to improved overall dietary health: western diets are often rich in processed foods, saturated fats, and added sugars, and have been associated with increased rates of obesity, diabetes, and cardiovascular diseases in Arctic populations.[78,90] This duality between dietary exposure to contaminants and food adequacy reflects the essence of the Arctic dilemma described in the previous section.

As no decrease in contaminant levels has been observed in wild animals in these areas (in some cases, even an increase has taken place), the reduced concentrations in human samples have been attributed to the substitution of these traditional food items with imported products.[9,22,27,42,56,58] The main determinants for this rapid dietary shift include among others:

- Financial costs related to acquiring subsistence foods, hunting and harvesting activities: fuel, equipment, etc.[79,80,88,91-93]
- Time limitations associated with work or school.[79,80,88,93]
- Impact of colonial processes and policies on food system and land-and sea-based subsistence practices (sedentarization processes, residential schools, urbanization, integration into market economy, changes in infrastructure, transport, etc.).[89,90,94]
- Loss of traditional culture, gap in intergenerational knowledge transmission related to hunting and harvesting practices, lack of training of future generations.[80,88,92]
- Lack of cultural connection, interest or knowledge in hunting and harvesting practices.[79,80,93]
- Concerns about the presence of contaminants in harvested animals.[81,88,95,96]
- Declining availability of animals and plants due to environmental changes, climate changes, changes in sea ice cover.[79,88,97]
- Time limitations associated with childcare and family commitments.[79,93]
- Physical inability to hunt.[93]
- Hunting regulations, bans, quotas and other wildlife management policies, laws, license restrictions.[79,98]
- Urbanization processes, living in an urban area.[79,99]
- Availability, affordability and ease of preparation of imported and processed market/store-bought foods.[87]
- Search for more food variety.[87]

While some of these factors impact both sexes similarly, this dietary transition has affected women more intensely than men. The reasons associated with childcare and lack of knowledge in hunting practices are reported by up to 40% women compared with less than 1% of men, which may indicate the importance of traditional gender roles in some northern communities and the difficulties that women experience in balancing domestic responsibilities.[93] Women have usually prepared meals and taken care of children and livestock, while also playing a key role in country food gathering by collecting berries and other edible plants. Meanwhile men have primarily engaged in other traditional activities such as hunting or fishing.[69,87,100,101] Although women are increasingly involved in hunting and harvesting, including challenging targets such as beluga,[76] gendered differences in country food selection are still evident: women generally prioritize low-risk, high-reward activities such as spring fishing or tidal gathering.[102]

Additionally, women in Arctic communities today usually have higher incomes and education levels than men,[75,103] which often limits their time to enroll in traditional activities such as hunting or harvesting and shapes their dietary habits.[104] The role of hunters and fishers therefore remains predominantly associated with men, and households without an active hunter or harvester tend to rely more on store-bought food products[105] and on food-sharing systems such as the community freezer (a storage facility where harvested traditional foods are stored and distributed within the community). As a result, a large proportion of women, particularly single women, rely on food-sharing networks (for example among their extended family) to access traditional foods.[79,92] The sharing of traditional food has historically played and continues to play a key role in preventing women and the elderly from experiencing severe food insecurity in Arctic communities[88,106]; however, in some communities, this practice has evolved from a communal tradition to a less frequent and more selective system, prioritizing close relatives and those who are most in need.[80] These shifts are largely driven by the reduced availability and rising costs linked to traditional foods,[92] and they result in women having more limited access to traditional foods. As discussed previously, fuel and equipment costs, time requirements, climate change, and seasonal unpredictability, among others, have contributed to making traditional harvesting less accessible, particularly for households without active hunters or sufficient economic resources.[79]

Gendered differences in the dietary transition explain a reduced consumption of traditional food by women compared to men, as documented in several studies. Table 1 provides an overview of the findings of 14 studies reporting the dietary habits of men and women: in nine of them, women were found to consume a smaller amount of traditional food items. Some of these studies reported numerical data on the proportion of population consuming traditional items, while others reported the number of marine food meals consumed per month, the daily amount of traditional foods, the percentage of traditional items composing the overall diet, or the ratio of $n-3$ to $n-6$ polyunsaturated fatty acids in plasma. Similarly, although no specific data were provided, the lower consumption of traditional food by women was also highlighted in three studies.

However, there is no clear consensus as regards these patterns: up to five studies reported similar dietary patterns between men and women, with only minor differences such as an increased consumption of fruits and vegetables by women.[10] The place of residence is also an essential factor influencing the diet of a given community, as it affects the availability of both market and traditional foods. Remote populations have more difficulties in accessing imported products and they rely more heavily on hunting and fishing activities, with more than 80% of traditional food consumption in some cases.[112] Conversely, larger towns and settlements, particularly in easily accessible areas, are more prone to adopt a "westernized" diet.[39,65] It has been described that women in large towns tend to adopt more westernized diets, which contributes to lower POPs levels compared to those of men.[39] Conversely, in places where men had reduced fish consumption—ie, less traditional diet, the differences in contaminant levels with women were also lower.[113] It has also been suggested that coastal populations rely more on marine mammals, which results in higher exposure to POPs.[114]

Overall, in Arctic communities, traditional food items account for an average of 12.8% of the total energy intake for women, and 1.4 times higher in the general adult population (18.0%), as shown in Table 2. However, the limited number of studies reporting these values (only five and four studies reporting independent values for women and children, respectively) and the

Table 1. Gendered differences of traditional food consumption in arctic communities.

Reference	Women	Men	Diff W/M	Indicators or statements from source article
Lower TF consumption by women				
Aker et al.[103]	26.70	73.30	0.36	Gender distribution of the population following a 'country food dominant' diet (%)
Long et al.[40]	0.26	0.39	0.67	n-3/n-6 ratio in plasma (indicator for marine mammal intake)
Deutch et al.[39]	8.95	12.18	0.73	Seal + whale + fish meals consumed per month
Jeppesen et al.[107]	22.21	29.69	0.75	Percentage of women or men to have a 'traditional food' diet (≥25% in energy from traditional food items)
Kuhnlein et al.[108]	2275	2710	0.84	Traditional food intake in grams per day. Adapted from figure in the original text
Wielsøe et al.[109]	13.00	15.00	0.87	Median intake of traditional food compared to the overall diet (% of total amount)
Bonefeld-Jørgensen and Long[110]	–	–	–	'In major towns […], women seem to have a higher intake of imported food.'
Dallaire et al.[50]	–	–	–	'Inuit men have a higher intake of traditional food compared to women (data not shown).'
Myers and Furgal[82]	–	–	–	'Women […] were less likely than elders and hunters to eat or have eaten marine mammal products or char.'
Similar TF consumption by men and women				
Ramirez Prieto et al.[111]	5.10	5.20	0.98	Average energy from traditional foods (% of total energy)
Egeland et al.[67]	56.60	57.30	0.99	Percentage of men and women who reported past-day traditional food consumption
Sorokina et al.[23]	65.00	61.30	1.06	Percentage of men and women consuming marine foods during the past month
Sheehy et al.[70]	39.50	37.00	1.07	Percentage of men and women classified as 'traditional eaters' (consuming more than 300 g of traditional food daily)
Deutch et al.[10]	–	–	–	'The food intakes of men and women were […] found to be very similar, deviating only for fruit and vegetables intakes of which were higher amongst women.'

Table 2. Percentage of total energy intake yielded by TF.

Population group	Range (%)	Average (%)
Adults (women + men) ($n = 13$)[a]	2.3 - 30.0	18.0
Women ($n = 5$)[a]	5.0 - 33.0	12.8
Children ($n = 4$)[a]	2.6 - 8.4	5.0

[a]Number of studies reporting values for each population group.

regional differences between populations living in different areas complicate a comprehensive analysis. Specifically, only two studies reported values for men, which provided insufficient data to support any meaningful evaluation. As an example of the role of location in diet, Berti et al. found that traditional food contributed between 5% and 33% of the total energy intake for lactating women in two different Canadian Arctic communities.[115]

The results presented in Table 2 should be interpreted with significant caution. As mentioned earlier, the limited number of studies and the substantial regional variations among different areas challenge the robustness of these findings, and the interpretation of these figures should be conservative given the limited statistical power of the available data. However, these findings still reflect a trend highlighted by many studies: women and children, on average, consume less traditional food than men. In the case of children, the difference is much more remarkable, with an average of 5% of the daily energy intake provided by these items.[65] Although the region also plays a key role in the amount of traditional food items consumed by children,[71] the dietary shift in younger generations is evident in most of these communities.[104]

Together with the unique elimination pathways described above, differences in dietary habits have been linked to the lower contaminant levels observed in women.[52] The role of diet in the contaminant exposure of women has been highlighted by several studies; within the female population, different dietary patterns can result in striking differences in their contaminant body burden, with concentration levels varying by up to 150-fold based on diet, according to a model proposed by Quinn et al.[116] An extreme example of gender differences in dietary patterns and their impact on health is the consumption of beluga tail meat exclusively by women during the "women's feast" in Nunavimmiut culture. This practice has been suggested as a possible explanation for the higher levels of selenoneine (present at high levels in beluga tail meat) observed in women compared to men.[76] This compound is a powerful antioxidant that helps minimize the effects of dietary exposure to methylmercury. Additionally, lower contaminant levels in women may also reflect the gendered impact of risk communication messages about chemical hazards in food, which are sometimes targeted exclusively at women.[117]

Plastic pollution in the arctic: micro and nanoplastics as emerging food contaminants to be further explored

As seen above, the existing Arctic biomonitoring literature has primarily focused on lipophilic POPs, PFAS, and trace elements, and research on plastic particles—including microplastics (<5 mm) and nanoplastics (<1 μm)—is more limited. However, their detection in various Arctic environmental media and the resulting exposure of Arctic biota to these pollutants are noteworthy.[118-120] Plastic debris found in aquatic ecosystems is a complex chemical matrix consisting not only of the polymer itself but also of additional compounds (eg, metals, organic, and inorganic compounds) that are intentionally added during manufacturing to provide specific characteristics or functions, as well as contaminants sorbed from the environment.[121,122] Thus, plastic particles can act as vectors (Trojan horse effect) for different pollutants, including those previously mentioned in this review, such as POPs, PFAS, and heavy metals. These contaminants may be released and dissociated from the plastic matrix during human digestion, potentially increasing their bioavailability and absorption in the body. To date, research on biological matrices has mainly examined macroplastic debris (>5 mm) and larger microplastics (>100 μm), which have been identified in the gastrointestinal tracts and/or scats of numerous marine species, including Arctic fish,[123] seals,[124] whales,[125] polar bears,[126] and walruses.[127] However, microplastics smaller than 100 μm and nanoplastics remain largely undetected due to analytical challenges, associated with the difficulty of isolating them from complex biological and environmental matrices, and the lack of standardized detection methods, despite their high likelihood of being present in Arctic food webs. Given the heavy reliance of Arctic populations on seafood-based diets, oral exposure to these contaminants is highly likely. In other non-Arctic populations, plastic particles have already been identified in faeces,[128-132] liver,[133] lungs,[134,135] urine,[136] and blood,[137] raising concerns about potential health effects. While most of these studies included both women and men (with the exception of[129]), they do not always specify whether micro- or nanoplastic detections came from male or female samples, making it unclear whether exposure differs by sex. Notably, plastic particles have also been detected in human tissues specifically linked to female physiology, such as the placenta[138-141] and breast milk.[142] It must be noted that this research remains limited, often relying on small cohort sizes and lacking detailed consideration of factors such as diet, lifestyle, and age. Additionally, methodological challenges, including the risk of analytical biases, contamination, and variability in detection techniques, may influence reported findings. Experimental studies on animal models indicate sex-dependent biological effects of micro- and nanoplastic exposure,[143,144] suggesting potential gender-specific exposure vulnerabilities. Thus, there is a need for future research in Arctic communities to investigate the presence, exposure and impact of these emerging contaminants through a gender-sensitive lens.

Conclusions

The lower chemical contaminant levels observed in women from Arctic communities are closely tied to their unique dietary behaviors, distinct from those of men, and to the existence of gender-specific elimination pathways for organic contaminants. Traditional food consumption, particularly of marine mammals, has long been associated with higher levels of lipophilic contaminants like POPs and heavy metals. Yet, women in these communities tend to consume fewer traditional foods leading to a reduced exposure to these substances. Despite these insights, significant gaps persist in our understanding of gendered dietary habits in these communities. The lack of comprehensive, gender-specific data undermines our capacity to fully grasp the dietary drivers behind contaminant disparities.

This limitation is particularly pressing given the so-called "Arctic dilemma," which highlights the challenge of balancing the invaluable nutritional and cultural benefits of traditional foods with their inherent chemical risks. The shift towards a more "westernized" diet, driven by factors such as the legacy of colonial policies, the impacts of global environmental changes, the declining availability of traditional foods, time or financial constraints, and urbanization, has led to reduced consumption of these items, particularly among younger generations and women. While this transition has contributed to reduce contaminant exposure, as evidenced by recent biomonitoring studies showing declines in POPs and heavy metals, it also raises concerns about the erosion of traditional dietary practices. These foods remain fundamental to Arctic communities, not only as a source of essential nutrients but also as pillars of cultural identity, food sovereignty, and overall dietary quality, as reflected in improved Healthy Eating Index scores.

To deepen our understanding of the mechanisms driving lower contaminant levels in women, future research must bridge these knowledge gaps. This includes conducting more gender-specific dietary analyses and biomonitoring studies across a broader spectrum of Arctic regions, expanding the range of studied contaminants—such as micro- and nanoplastics—and adopting a holistic approach to the Arctic exposome. Additionally, given the distinct exposure profile of Arctic populations (as a result of their unique combination of traditional lifestyles and dietary exposure), they represent a valuable case study of the broader impacts of chemical exposure. Therefore, future exposome studies should consider the inclusion of these communities in their target population groups as a means to capture the full range of variability in diverse human contexts.

Author contributions

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Supplementary material

Supplementary material is available at *Exposome* online.

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Conflict of interest

The authors have no conflict interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript or in the decision to publish the results.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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