HOW EFFECTIVE ARE CURRENT REGULATIONS AND MANAGEMENT STRATEGIES IN REDUCING HEAVY METAL POLLUTION IN THE CANADIAN ARCTIC

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Table of Content

Table of Figures

Table of Tables

1. Introduction

The Arctic region, spanning nations such as Canada, Russia, the United States, Norway, and Iceland, is characterized by its extreme climate and limited accessibility and has seen limited research on heavy metal pollution[1]. There has been relatively less research in this area due to the challenging climate and the inaccessibility of remote regions, which poses significant overhead costs for conducting scientific studies[57]. This extreme weather is felt all over the 1.4 million square kilometers of the Canadian Arctic and encompasses many ecosystems with substantial natural resources, and cultural legacy[58]. It includes the territories of Yukon, Nunavut, and the Northwest Territories, as well as some portions inside provinces such as Ontario, Manitoba, and Québec, accounting for more than 40% of total Canadian territory. It is home to more than 630 Indigenous communities, including the Inuit and First Nations tribes such as the Cree, Acho Dene Koe, Aklavik, and Métis. This extreme weather had defined the living conditions for the Arctic communities but also the distant relationship from researchers who are reluctant to conduct research due to the extreme weather making accessibility hard and working conditions difficult[2].

Canada's economy heavily relies on mining and energy exploration, which are fueled by the country's vast natural resources. The region is rich in minerals, oil, and gas, making these industries critical to its growth and development. These industries generate employment opportunities, contribute significantly to Canada's GDP, and drive economic expansion countrywide[63]. In 2020, the Canadian natural gas and oil industry contributed $105 billion to Canada's GDP and created approximately 400,000 employment opportunities across the country. The production value of the mining industry has increased significantly, with the mining sites in the Northern territories of Yukon and Nunavut in the Arctic contributing over $4.8 billion to the value of material output[3].

The Arctic's captivating landscapes, diverse wildlife, enchanting Northern lights, and distinct cultural communities attract a thriving tourism industry with enormous economic benefits. This sector provides tourists with unique experiences and contributes to the growth of local businesses, infrastructure, and economic opportunities stemming from the region's rich cultural heritage and natural beauty. According to a 2017 Conference Board of Canada report, approximately 305 million Canadian dollars (CAD) and 3,800 jobs were generated by tourism and non-tourist activities in Canada's northern territories (Yukon, Northwest Territories, and Nunavut)[64]. The Canadian Arctic's economic relevance goes beyond natural resources and mining. Through the North-west Passage, the area facilitates marine transit and resource development between North America, Europe, and Asia. As Arctic Sea ice melts, the North-west Passage becomes more accessible, cutting shipping times and costs[62]. This accessibility may enable new economic, resource exploitation, and international trade possibilities[60]. However, it raises worries about increasing maritime traffic and the related hazards of oil spills and other pollutants that might contribute to damaging the Arctic's fragile marine ecosystems[1]. This change to the food web impact Indigenous livelihoods, wildlife habitats, and customary ways of life[1,2].

Culturally important indigenous communities dwell in the Canadian Arctic. Over millennia, these Arctic communities have developed distinct cultural identities, dialects, and traditional knowledge systems closely tied to their environment. Indigenous communities revere the Arctic for its centuries-old stories, histories, and lessons[62]. These practices go beyond sustenance, including a profound grasp of ecological interconnectedness, sustainable resource management, and human-nature balance[61]. Heavy metal contamination in the Arctic may damage seafood, marine animals, and migrating birds, which indigenous populations depend on culturally and as a means of survival and part of their cultural activity[58]. Heavy metal pollution affects more than physical health. Traditional food supplies are contaminated, disrupting cultural traditions, indigenous knowledge transfer, cultural identity, and pride. Indigenous knowledge about the Arctic's ecology and resiliency comes from years of observation, experience, and cultural preservation, all of which can be harmed by inaction to protect their communities[62]. The comprehensive and regional viewpoints on heavy metal pollution's effects that can be learned from Indigenous communities who are the original land keepers provide a natural approach that can be combined with scientific knowledge[4,10]. International sustainability and environmental protection depend on cultural heritage and indigenous rights. The UN Declaration on the Rights of Indigenous Peoples (UNDRIP) protects indigenous traditions, practices, and territory[9]. Indigenous land rights and stewardship are essential for active involvement in Arctic resource management and environmental protection decisions[63]. Thus, including indigenous communities is necessary to enhance knowledge, build trust and provide culturally relevant solutions. Indigenous participation as land knowledge holders in collaborative research initiatives is more likely to enhance a sustainable and equitable solution that accounts for minimal invasive land damage[51].

As an indication of worldwide environmental changes and a unique habitat for investigating heavy metal contamination, the Canadian Arctic has unsurpassed value. The region's severe cold, extensive ice fields, and frozen tundras make it one of the most susceptible to climate change. The Arctic affects worldwide climate patterns and is a harbinger of human activity's global effects. The Arctic has seen fast climate change, including sea ice loss and extensive weather shifts[62]. Sea levels are increasing due to melting glaciers and sea ice in the Arctic. These changes damage habitats and impact polar bear, seal, and migratory bird movement patterns, affecting ecosystems and animals. In addition to being a climate change indicator, the Arctic absorbs long-range contaminants, including heavy metals. Industrialized areas emit pollutants hundreds of kilometers distant, which air currents carry to the Arctic and deposit as atmospheric mercury[64]. This phenomenon causes Arctic wildlife and plants to bioaccumulate heavy metals, which might harm animals and indigenous societies that use these resources[18].

Arctic heavy metal pollution is distinctive due to its isolation and inaccessibility, leading to slow response and limited research to understand the degree of damage. Isolation may delay pollution identification and control, enabling toxins to persist and spread throughout the environment. On-site scientific research, modern monitoring methods, and worldwide cooperation are needed to understand heavy metal fate and transit in this distant environment[62]. Due to its unique environmental dynamics, heavy metal contamination and natural processes interact complexly in the Arctic[4]. Mercury in the atmosphere may undergo numerous changes before being deposited in the Arctic by sea ice and phytoplankton, raising methylmercury levels in Arctic surface waters, which slowly makes its way into the food web, bioaccumulating slowly firstly through predators like seals, and polar bears, then to humans that consume these sea creatures. This change to the food web impact Indigenous livelihoods, wildlife habitats, and customary ways of life[4].

Heavy metals in the right proportion, play a role in environmental upkeep and human health. Heavy metals like zinc, iron, and magnesium are vital for biochemical and physiological processes, and their deficiency can result in disorders and syndromes in living organisms[64]. While beneficial in the right proportion, they can also be detrimental to the environment and human health[58]. This is due to their persistence and ability to bioaccumulate, requiring careful regulation and management[16]. Heavy metals in abnormal proportions damage the Arctic ecosystems as well as human health. Heavy metals may bioaccumulate in Arctic marine and freshwater species via contaminated water and sediments. These contaminants may disrupt aquatic creatures' behavior, reproduction, and survival, impacting food chains and ecosystem dynamics[62]. Heavy metal bioaccumulation in apex predators like polar bears and arctic foxes increases the risk of ecological disturbances that cascade to other species and the ecosystem.

Heavy metal contamination in the Arctic may also have global effects. Arctic-breeding migratory birds may carry heavy metal pollution to other regions, impacting ecosystems and biodiversity. Comprehensive and coordinated Arctic heavy metal pollution mitigation involving arctic countries and heavy metal polluters is needed to address the release and reduce long-range transport of mercury and lead that affect the Arctic regions[18].

Climate change is causing fast and unexpected changes in the Arctic, resulting in a complicated interaction with heavy metal contamination that requires immediate action. The Arctic climate's warming affects heavy metal discharge, transit, and distribution[62]. The delicate equilibrium governing heavy metal distribution is broken as temperatures increase, permafrost thaws and sea ice melts, threatening the Arctic environment and its people[14]. While a comprehensive study is needed to understand the changing dynamics of heavy metal pollution in the Arctic, a review of current policies and management measures is required to enhance response and provide adjustments to protect the ecosystem and populations[63]. The Arctic is warming twice as rapidly as the rest of the planet. These variations affect ice cover, precipitation, and growing seasons, releasing heavy metals stored in these deposits, causing a positive feedback loop[60]. Heavy metal pollutants infiltrate water bodies and ecosystems when permafrost thaws, this discharge worsens environmental changes, exacerbating regional warming and affecting Arctic animals and populations. The relationship between heavy metal contamination in the Arctic and climate change is complex and interconnected. Changes in weather patterns, like modified wind patterns and precipitation regimes, can affect the long-distance transit of contaminants, including heavy metals, to the Arctic. As a result, pollution from distant sources may deposit on the Arctic landscape and aquatic bodies. Changes in sea ice dynamics from climate change can have an impact on the water patterns and thus the movement of heavy metal deposit[64].

Mercury (Hg) and lead (Pb) are common leading contaminants released into the environment due to climate change and affecting the region's environment and habitats[14]. Mercury is one of the most common heavy metals present in the Arctic region, with some of its sources of discharge into the atmosphere from power stations, trash incineration, artisanal gold mine and naturally through volcanic eruptions. Atmospheric mercury undergoes numerous processes before being deposited in Arctic water bodies and sediments[63]. Aquatic phytoplankton may also release toxic methylmercury, which is eaten by top predators like seals, polar bears, and large fish, contaminating the food web[64]. Indigenous communities that rely on traditional subsistence hunting and fishing are at risk of Mercury as in fetuses and young children, methylmercury may damage the neurological and physical development[21]. The melting of glaciers, sea ice, and permafrost in the Arctic due to climate change has major consequences. When these frozen components thaw, they release heavy metals previously trapped over time. This raises concerns about their potential impact on the environment and biology[21,49]. While Lead (Pb) pollution is primarily associated with coming from human activities such as industrial processes, mining, and burning fossil fuels, past lead emissions continue to affect the Arctic even after lead usage in gasoline and other items such as pipes has been reduced worldwide due to long-range atmospheric transmission and remobilization from soils and glacier[64]. Aquatic and terrestrial ecosystems are in danger from lead contamination in water and soil as Lead exposure, even at low levels, may cause neurological abnormalities, developmental delays in children, and cardiovascular illnesses[62, 63]. Due to their traditional lives and substantial relationship to the environment, Arctic indigenous groups are in danger of lead poisoning through their water directly but through their livestock that drink from lead-contaminated water [64,14].

New policies and management strategies must account for the fast-changing Arctic environment due to climate change and remain adaptive for unforeseeable changes that may occur[61]. Due to inaction, Climate change is becoming less of a concern and more of a reality. While the damages posed by heavy metal pollution because of climate change cannot be eradicated, they can be managed and made sure communities are well-equipped to handle all possible threats to their survival. This research looks to analyse existing commonalities from available data on heavy metals to highlight adaptable measures and overload gaps in current policies and management strategies of heavy metal pollution in the Arctic[62].

1.1 Purpose and Significance of the Research

This study focuses on examining how Canadian Arctic regulations and management strategies have impacted heavy metal pollution in the region. By exploring the complex relationship between heavy metal pollution and climate change, this project aims to assess the effectiveness of current management and regulation methods and recommend future modifications that could enhance these strategies.

The research aims to increase our understanding of the effects of heavy metal pollution on the Arctic ecosystem, as well as on human health and Indigenous communities' culture and way of life. Indigenous communities often face disproportionate exposure and vulnerability to heavy metal pollution due to their reliance on traditional food sources, close connection to the land & water, and cultural practices that involve harvesting and consuming locally available resources. A prominent example of heavy metal impact is the Asubpeeschoseewagong First Nation, also known as Grassy Narrows First Nations, which had been affected by mercury contamination through their local waterways[4]. This left a lasting impact on the community, harming their populations, livestock, and cultural relationship with their environment[4]. The results of the study will have significant implications for governments, private stakeholders, and the Arctic population, influencing their actions and decisions toward effective regulations and sustainable management strategies for the region. To achieve the research objectives, it is crucial to identify the research questions that will guide the study.

1.2 Objectives and Research Questions

This literature-based research aims to address the research question:

"How does the changing climate impact the effectiveness of current regulations and management strategies in reducing heavy metal pollution (Mercury and Lead) in the Canadian Arctic, and what are the potential adaptations that can be implemented to mitigate these impacts?"

The research objectives of this study encompass a comprehensive assessment of heavy metal pollution in the Arctic, with a specific focus on

1. Evaluating current regulatory and management policies, including the Northern Contaminants Program (NCP), Canadian Environmental Protection Act, 1999 (CEPA), and Canadian Metals and Mining Effluent Regulations (MMER),
2. Understanding the impact of climate change on pollution levels,
3. Identifying potential adaptations to mitigate these impacts,
4. Establish the relationship between climate change and the increasing levels of heavy metal pollution in the region,
5. Evaluate the adequacy of current measures in addressing the emerging dangers.

In assessing the effectiveness of regulations and management strategies, this research also acknowledges the challenges and limitations associated with their implementation while exploring potential adaptations and innovations that can be adopted to mitigate the impacts of climate change on heavy metal pollution in the Canadian Arctic. This includes considering the feasibility and barriers associated with implementing these adaptations and the long-term implications of heavy metal pollution due to climate change on the region and human health if effective measures are not implemented promptly. Moving forward, it is essential to acknowledge the limitations of this study to provide a balanced perspective.

2 Literature Review

2.1 Current Regulations and Management Strategies for Reducing Heavy Metal Pollution in The Arctic

Research by Houde in 2020 suggests that reducing the contamination caused by heavy metals, particularly Mercury (Hg) and Lead (Pb), in the Canadian Arctic requires effective regulation and management techniques[6]. The effectiveness of treatments may be influenced by additional problems arising from a developing environment. This section explores the efficacy of existing management strategies and legislative measures in addressing the issue of heavy metal pollution within the framework of a dynamic climate. The Northern Contaminants Program (NCP) plays a pivotal role in mitigating and overseeing the presence of heavy metal pollution within the Canadian Arctic region. The system performs comprehensive analysis and offers significant data on pollution levels and patterns[6]. The Arctic's heavy metal contamination is addressed through the NCP, a thorough effort. It undertakes research, monitoring, and risk analysis to evaluate the amounts and effects of pollutants, especially heavy metals, on the natural environment and indigenous communities. The initiative encourages regulations based on scientific findings and supports the development of management methods to decrease exposure to heavy metals.

Mercury and Air Toxics Standards (MATS) also creates emission regulations, monitoring, reporting, and compliance rules. It is a controlling enterprise to lower mercury and other dangerous air pollutant discharges from Industries in Canada and the US Arctic[7]. Despite not being specific legislation, Environmental Impact Assessments (EIAs) are essential for controlling the pollution caused by heavy metals. EIAs are performed on significant industrial undertakings, such as mining activities, to evaluate potential environmental impacts, such as heavy metal contamination. These investigations contribute to reducing heavy metal contamination risk by developing and implementing mitigation solutions and ensuring compliance with applicable laws and standards.

The Canadian Arctic Contaminants Assessment Report (CACAR), which evaluates the effectiveness of present laws and management practices, contributes to this understanding. The Canadian Metals and Mining Effluent Regulations (MMER) manage metal emissions from mining operations. The MMER, a Fisheries Act regulation, places restrictions on the discharge of wastewater from metal mines[8]. By defining discharge limitations for chemicals like arsenic, copper, lead, nickel, and zinc, it explicitly addresses heavy metal pollution[8]. The regulations mandate that mining companies measure and record their effluent emissions, implement best management practices, and comply with the CAAQS. This was created by the Canadian Council of Ministers of the Environment and included air quality criteria for a variety of pollutants, including heavy metals[9]. These standards set maximum permitted levels of heavy metals in ambient air to safeguard the ecosystem and human health. By reducing the atmospheric accumulation of heavy metals in the Arctic, adherence to these criteria helps control emissions from economic activities. These regulatory frameworks are essential for lowering pollution, but they must also be assessed considering how climate change affects the environment and how fast it is evolving. Thus, CACAR evaluations need to be expanded to be more preventive rather than reactive in evaluating the performance of various frameworks and strategies in lowering mercury exposure and emissions in the context of the Canadian Arctic.

2.1.1 Mercury And Lead as Main Pollutants in the Canadian Arctic

The primary contaminants in the Canadian Arctic are known to be mercury and lead, which provide severe dangers to both the ecosystem and public health. The main human activities that produce mercury are mining and burning fossil fuels[10]. Mercury is also transported vast distances by the atmosphere and accumulates in Arctic ecosystems. This deposit in the ecosystem is dangerous for food web balance and Indigenous communities who rely on obtaining their food directly from the environment, such as seals and fish. Long-distance atmospheric transport carries lead from industrial operations to the Arctic, where it can contaminate water, soil, and harm animals. ASGM gold mining and industrial sources account for 75% of anthropogenic Mercury (Hg) deposition[10]. Neurological impairment, developmental issues, and diminished cognitive function are some of the damaging impacts noted to occur within people. Climate change makes the Arctic ecosystem and its inhabitants much more susceptible to heavy metal pollution. To create efficient laws and management plans, it is essential to comprehend the behavior, distribution, and sources of mercury and lead in the Arctic[11]. This section will critically examine the present understanding of mercury and lead contamination in the Arctic. It will include information on their sources, modes of transportation, rates of accumulation, and potential adverse effects on the ecosystem and public health.

2.1.2 Existing Regulations on Mercury and Lead Pollutants in the Canadian Arctic

The US Environmental Protection Agency (EPA) has Mercury and Air Toxics Standards (MATS), a regulatory framework tasked with reducing mercury, lead, and other hazardous air pollutant discharges from power companies in Canada and the US Arctic[12]. The policy creates emission regulations and monitoring, reporting, and compliance rules. Due to the various research and studies, mercury has detrimental impacts on human health and the environment[13], MATS explicitly targets reducing mercury emissions. The program seeks to safeguard air quality, lower public exposure to mercury, and lessen any resulting health hazards by limiting mercury emissions[14]. Research in 2020 by Aldy on security regulatory analysis shows the program's approach ignores "co-benefits," or economically significant but indirect public health advantages, in a way that is at odds with basic economic principles[14]. Part of this research involved identifying significant sources of direct health benefits from mercury emission reductions that need to be considered in policy implementation[15]. One suggested action from the agency is the installation of pollution control monitors by power plant companies to monitor mercury emissions and implement best practices to achieve the MATS regulations. Results from the agency highlight that their various proposed regulations have played a role in the substantial reduction of mercury from sources of energy production and thus improved air quality[15].

The Northern Toxins Program (NCP) is a comprehensive project to monitor and reduce toxins in the Canadian Arctic, including weighty metals like mercury and lead. The territorial and federal organizations, research, and academic groups combined efforts to form the NCP in 1991. According to Muir et al. (2023), the main objective of NCP is to evaluate pollution trends and concentrations in the Arctic ecosystem and their impacts on public and comprehensive health [16]. The NCP gathers information on heavy metal concentrations in indigenous communities' air, water, soil, biota, and traditional food supplies through extensive monitoring. The NCP is significant for figuring out how well existing rules and management are working to reduce pollution from heavy metals. One of the study projects and tracking programs started by the NCP gives information about how well MMER works to lower mercury levels. The assessment recorded the presence of low identification frequencies of chlorpyrifos (CPY), a pesticide linked to mercury contamination in Arctic Fish species"[16]. A statistical analysis was done on this in a study replacing non-detects with a 12-detection limit (12 DL) and revealed the existence of CPY in alarming concentration in Canadian arctic water and Air. Whilst the study was indicative of the MMER in monitoring and managing heavy metal pollution output, it is also indicative of the gap policy needs to contain the issue[16]. The program evaluates the effectiveness of regulatory actions taken pursuant to the Canadian Metals and Mining Effluent Regulations (MMER) and other statutes through research and collection of data for analysis. Additionally, the NCP recognizes the hazards of heavy metal contamination in the Arctic because of climate change. It investigates potential modifications that could be made to mitigate the effects of climate change, such as establishing adaptable management systems, promoting sustainable behaviors, and supporting community-based strategies. The NCP's comprehensive strategy combines scientific research, monitoring, and stakeholder engagement, contributing to a better understanding of the dynamics of heavy metal contamination in the Canadian Arctic. The information facilitates the development of realistic management plans and laws that safeguard the fragile Arctic ecosystem and the well-being and health of indigenous inhabitants.

The Canadian Arctic Contaminants Assessment Report (CACAR) is also a vital tool for understanding the extent of contaminants, particularly metals such as mercury. CACAR thoroughly evaluates the levels, distribution, and trends of several pollutants in the area in its periodic publications. The effectiveness of present laws and management plans for decreasing heavy metal pollution is critically assessed by CACAR. CACAR evaluates the results of regulatory measures like the Canadian Metals and Mining Effluent Regulations (MMER) by looking at the data gathered through monitoring programs and research studies[17]. The CACAR recognizes the critical need to address how climate change impacts the heavy metal contamination in the Canadian Arctic. It highlights how important it is to change the policies and management methods that are now in place to decrease the consequences that can result in the short and long term[17]. By highlighting the vulnerabilities and potential threats posed by climate change, policymakers, stakeholders, and communities are made aware of the need for adaptable methods to address heavy metal contamination.

Moreover, a critical regulatory framework primarily aimed at preventing the release of discharges from mining activities and metals in the Arctic region is the Canadian Metals and Mining Effluent Regulations (MMER). According to Etteieb’s research, these regulations from MMER set precise guidelines for managing and reducing the impact of pollutants, especially heavy metals, on the surroundings[18]. The MMER establishes monitoring systems and sets effluent limits to ensure compliance. The EDL under the MMER is set at 0.1 micrograms per litre (µg/L) for metal mines with a design flow rate of 50 cubic meters per day or more[8]. This limit is stricter than the maximum acceptable concentration of mercury in drinking water by Health Canada, which is 1.0 µg/L[19]. Similarly, the EDL of LEAD under MMER is set at 0.5 µg/L for metal mines with a design flow rate of 50 cubic meters per day or more. The acceptable maximum concentration of lead in drinking water by Health Canada is 5.0 µg/L. The EDL under the MMER shows stringent control on heavy metal discharge to protect human health but also prevent environmental contamination[8].

In addition, the Arctic and Northern Policy Framework (ANPF) is a broad strategy initiative that directs the administration and supervision of the Canadian Arctic region. It aids in addressing current restrictions on contaminants in the Canadian Arctic, particularly heavy metals. As mentioned by Kikkert, the ANPF highlights the need for efficient pollution management measures while acknowledging the environmental difficulties the Arctic faces due to its vulnerability to climate change[20]. It encourages participatory methods of engaging stakeholders, including Indigenous groups, to create and implement adaptable measures to lessen the effects of heavy metal contamination[20]. Policymakers work to improve the resiliency of the Arctic ecosystem, safeguard public health, and assure equitable growth in the face of shifting environmental circumstances and evolving pollution concerns by adopting the ANPF rules.

2.1.3 **Potential Impacts of Climate Change**

The impact of climate change on lead and mercury contamination in the Canadian Arctic is significant. This impact was highlighted by Adhikari's 2020 research, in which he stated that altered precipitation patterns, dissolving permafrost, and rising temperatures could directly impact the bioaccumulation, transport, and discharge of these heavy metals in the region[21]. Lead and Mercury may become more accessible as permafrost thaws, releasing previously frozen contaminants and organic waste into the environment. The transit and deposition of these contaminants can be affected by variations in precipitation patterns, which can change how they accumulate and are distributed in Arctic ecosystems. In addition, by altering the physiology and behavior of species, climate change has the potential to impact lead and mercury pollution indirectly. For instance, increasing temperatures may make certain heavy metals more hazardous and bioavailable to Arctic animals, such as fish and fauna, which could result in bio magnification. Resolving the issues of heavy metal pollution requires long-term monitoring, interdisciplinary research, and collaboration between indigenous groups, policymakers, and scientists in order to reduce the potential effects and protect the fragile Arctic ecosystem and the welfare of its inhabitants.

As climate change poses a significant threat it is important to review and evaluate the viability of the current management plans and laws regulating mercury and lead pollution in the Canadian Arctic. Climate change can affect the bioavailability, and transport of these contaminants in the ecosystem, which could compromise the efficacy of current controls[22]. Increased mercury and lead inputs into Arctic ecosystems can be caused by releasing previously trapped contaminants due to melting permafrost and rising temperatures. It worsens pollution levels by upsetting the delicate balance between sources and sinks of pollutants. Increased storm activity and modified precipitation patterns can also transfer mercury and lead from land to aquatic systems, leading to higher concentrations in aquatic species and water bodies. Regulations and management measures would need to be advanced and incorporate a collaborative pollution ecology frontier that supports the creation of novel adaptive environmental protection strategies[22]. According to research by Ore in 2021, changes in habitat accessibility, ecological interactions, and species composition caused by climate change may impact Arctic creatures' susceptibility and exposure pathways to mercury and lead pollution[23]. Changes in species distributions, feeding habits, and migration patterns may affect how these toxins are biomagnified and bioaccumulated, endangering animals and possibly affecting the health of Arctic communities that depend on traditional food sources. Given these intricate relationships, it is crucial to modify and reevaluate present policies and management plans to consider the changing climate and its impact on mercury and lead contamination in the Canadian Arctic. It necessitates a comprehensive strategy involving ecological modelling, climate projections, and incorporating indigenous tribes' traditional knowledge.

Several alternative adaptations can be considered to lessen the effects of climate change on the heavy metal contamination in the Arctic. These modifications have to be geared towards improving the efficiency of current laws and management techniques while considering the difficulties brought on by climate change. One possible adaptation is creating and implementing comprehensive surveillance systems that monitor alterations to the patterns of heavy metal pollution and provide information on timely decision-making. “It is advised that exploration techniques and technology be upgraded to reduce on-site pollution from metals as well as off-site metallic pollution during disposal or refining”[23]. Extensive research has called for a comprehensive monitoring system that considers a wide range of environmental compartments, including soil, water, air, and biota. To understand the dynamics of heavy metal contamination more comprehensively, it is necessary to incorporate conventional ecological wisdom from indigenous populations.

2.2 Changes to Regulation and Management Strategies

Changes to regulation and management systems are crucial to address the effects of climate change on heavy metal pollution in the Canadian Arctic. According to research by Adnan in 2022, to guarantee that existing restrictions successfully reduce pollution risks, they must be reevaluated considering the changing environment[24]. Rules ought to be specifically updated and altered to reflect the most recent findings in science about the effects of climate change on lead and mercury pollution in the Canadian Arctic[24]. This entails considering climate change issues when establishing pollution reduction strategies and modifying emission restrictions to accommodate changing conditions and lack of wholesome knowledge. This would also involve the utilization of adaptive management strategies to aid in addressing fresh and unplanned problems brought on by climate change.

There has been a rise in demand for cooperation and intellectual sharing between Canadian stakeholders and foreign partners in the fight against lead and mercury pollution. Adnan emphasizes the importance of incorporating scientific experts, indigenous communities, business executives, and government organizations into decision-making processes in his research[24]. By embracing a range of opinions and skills, Adnan believes a practical approach and be developed to address various stakeholders' concerns of the region. Subsequently, the development of novel techniques and technologies that reduce the consequences of heavy metal pollution caused by climate change depends on investment in research and development. This could entail looking into alternative pollution control strategies, promoting sustainable activities, and pushing for the development of greener technologies[25]. It is possible to effectively control heavy metal pollution in the Canadian Arctic despite changing climatic circumstances by consistently pursuing excellence and embracing sustainable techniques.

2.3 Technological Solutions and Community-based Approaches

The effects of climate change on lead and mercury pollution in the Canadian Arctic are being mainly addressed through technological innovations and community-based strategies. As mentioned by Houde in his study on contributions and perspectives of Indigenous people to studying mercury in the Arctic, advanced pollution control technologies implementation is one of the ways modern sciences have benefited from technological advancement to understand the impacts and projecting damages the Arctic region would face without effective action[26]. Some of these technological solutions have involved employing cleaner, efficient production methods, enhanced waste treatment procedures, and cutting-edge filtering systems in industries operating in strategic areas to control the release of lead and mercury to the environment. While technology can provide a cutting-edge policy, it lacks day-to-day understanding of how the changes affect communities. Thus, new policies are an opportunity to utilize Indigenous knowledge in addition to scientific breakthroughs to preserve culture and regional infrastructure.

Community-based projects frequently integrate traditional wisdom with scientific understanding to provide effective and culturally appropriate solutions. Community involvement encompasses several forms of participation, such as partnerships in collaborative decision-making processes, knowledge-sharing efforts, and monitoring programs. Improving the efficacy and acceptance of management systems is feasible by empowering local populations and incorporating them in pollution control initiatives. Community-based strategies and technical solutions both mutually and complementarily reinforce one another. "Native Americans make significant contributions to Arctic Mercury (Hg) study and monitoring"[27]. To examine the impact of climate change on heavy metal contamination in the Canadian Arctic, it is plausible to develop comprehensive and sustainable strategies that integrate advanced technology and actively engage local communities[28].

2.3.1 Feasibility and Effectiveness of Potential Adaptations

Considering the feasibility and efficacy of potential adaptations is crucial for addressing the impacts of climate change on heavy metal contamination in the Canadian Arctic[14]. These adaptations cover a wide range of tactics from various sectors intended to lessen the negative impacts of climate change on current management and regulation practices.

According to Duchenne-Moutien, the potential adaptations are evaluated in terms of technological viability, economic viability, and environmental sustainability[29]. It necessitates considering how suggested actions work with existing infrastructure, available resources, and long-term viability in a changing environment. The success of adaptations is also evaluated in terms of their capacity to safeguard human health and the Canadian Arctic surroundings and reduce heavy metal pollution[29]. Possible adaptations include supporting alternative technologies, improving monitoring and surveillance systems, encouraging international collaborations, enforcing higher emission regulations, and incorporating climate change considerations into policy frameworks. In response to the research question of protecting the Canadian Arctic from the effects of heavy metal pollution aggravated by climate change, it is essential to assess the viability and efficacy of these adaptations.

Supporting other technologies is a potential adaptation. The Canadian Arctic can gain from more effective and focused solutions to eradicate heavy metal contamination by funding and supporting alternative technologies, such as cutting-edge remediation techniques or treatment approaches. Compared to conventional approaches, these alternative technologies are frequently shown to be more effective, producing better results in terms of pollution reduction[30]. Increasing the accuracy and timeliness of the detection of sources of pollution and trends is possible by improving surveillance and tracking systems. Monitoring systems can offer an improved comprehension of the dynamics of contaminants such as heavy metals by utilizing cutting-edge technologies, remote sensing, and data analytics. With this expanded knowledge, targeted interventions can be made, and general management and reaction tactics can be improved.

Enforcing stricter surveillance and measures can drastically reduce pollution discharges at their origin. This can be accomplished by strengthening emission laws. Heavy metal discharged into the environment can be reduced by establishing stronger controls on manufacturing processes and putting in place strong compliance mechanisms. By including climate change concerns in policy frameworks, Leaders can proactively address the interaction between global warming and heavy metal pollution by incorporating considerations for climate change into policy structures. This integration into policy makes it possible to formulate comprehensive plans and strategies that consider the changing climatic circumstances and their potential effects on the pattern of pollution from heavy metals.

3 Methodology

3.1 Research Design

This study's primary objective was to determine how the Canadian Arctic's changing climate affects the efficiency of current management practices and policies for decreasing mercury (Hg) and lead (Pb) contamination. The investigation also investigated possible adjustments that may be made to lessen climate change's consequences. As a result, it was necessary to select an appropriate study design that could fulfill these aims.

For that reason, a systematic review with a qualitative approach was deemed appropriate. Comparatively, qualitative research entails gathering and gaining valuable insights from non-numerical data, whereas a systematic review employs previously available data to conclude a response to a specific research question using a systematic process [31]. This methodology was preferred because it includes well-defined criteria for the synthesis of data from existing literature with minimal bias[32]. Moreover, the formulation of conclusions relies on the analysis of numerous interconnected studies. Consequently, this research design would provide a more comprehensive outlook on the possible adjustments that could be employed to address climate change and evaluate the efficacy of existing regulations and management approaches in mitigating the issue of heavy metal contamination, specifically pertaining to Mercury and Lead, in the Canadian Arctic. Additionally, it provides a cost-effective and time-efficient alternative to primary research. Nevertheless, the efficacy of this design is contingent upon a meticulously constructed procedure.

As a result, a systematic design was created to achieve a well-defined process. The design comprised three essential elements: the search strategy, data analysis, and the limitations, which together form a rigorous and comprehensive analysis of the information available from various sources. As discussed below, these components extensively describe how the data collection and synthesis process was carried out.

3.2 Search Strategy

A systematic search strategy was employed to identify relevant search engines to obtain related scholarly articles, government reports, official documents and case studies related to heavy metal pollution, specifically Mercury (Hg) and Lead (Pb) in the Arctic. This strategy follows the guidelines outlined by the Preferred Reporting Item for Systematic Reviews and Meta-Analysis (PRISMA)[33,34]. These guidelines involve identifying multiple sources using keywords in a database search, screening the identified studies to distinguish duplicates and those that do not meet the inclusion and exclusion criteria, and further assessing the screened sources for quality and eligibility. The systematic approach of this methodology has its advantages.

For example, it ensures a transparent and comprehensive approach to the literature relevant to the specified topic, in this case, the effectiveness of regulation and management strategies in reducing heavy metal pollution in the Arctic, specifically Mercury (Hg) and Lead (Pb). Therefore, considering these principles, this study's search strategy and data collection consisted of five primary steps:

I. **Search Using Keywords:** The process began with identifying sources through database search using search keywords. A selection of relevant keywords and terminology was identified and chosen based on their direct relevance to the research topic and objectives, encompassing heavy metal pollution, the Arctic region, and specific elements such as mercury and lead. These keywords include the terms “heavy metal,” “mercury (Hg),” “lead (Pb),” “pollution,” “Arctic,” “Northern region,” “Yukon,” “Nunavut,” “Canadian North,” “ Arctic Adaptation,” “Arctic Mitigation,” “Canadian arctic,” “Canadian Arctic

Policy," "Arctic + Policy + in Canada," "Canadian Arctic Report," "Indigenous + Arctic + Community," "Arctic + Inuit + Communities," " Aboriginal + Arctic + Community." These keywords and terminologies were established per the PRISMA methodology as they would capture a range of studies and documents that can comprehensively answer the research questions and meet the paper's objectives. They were identified and selected based on their direct relation to the scope of this research.

For instance, the keywords and terminologies target studies that have directly addressed how regulation and management strategies have responded to reduce heavy metal pollution, specifically Mercury (Hg) and Lead (Pb), in the face of climate change. In addition, it is aimed at various research that has focused on the Canadian Arctic region and prominent places in the region, such as known weathering sites, current and/or previous mining areas, Yukon, and Nunavut. However, the identified sources and databases had to be assessed for reliability and quality to be included in further analysis.

II. **Critical appraisal, quality and reliability of sources and database:** The critical appraisal process is a vital component of the PRISMA methodology, ensuring the reliability and credibility of selected studies, papers, and data by evaluating factors such as study design, data collection method, publication year, and utilizing trusted search engines and databases[33,34]. The factors involved in this process included scrutinizing the study design, the data collection method, the year the paper was published, sample size, generalizability, and potential bias. The checklist for this paper looked to ensure that papers released were as recent as possible and, if not, was still relevant such that they had either been corroborated by other papers or used by other research to advance the study area. Moreover, to ensure the peer-reviewed articles, studies, and datasets were trustworthy, the primary search engines used were PubMed, Scopus, Web of Science, Science Direct, Government of Canada, Statistic Canada, and Climate Change Canada.

Other secondary search engines involved university libraries such as uOttawa OMNI, ASTIS, Climate Atlas Database, and Arctic Portal. It was essential to search through multiple engines and explore various research methodologies and research designs to enhance the overall reliability and comprehensiveness of the literature utilized. After that, the sources needed to be scrutinized further based on the inclusion and exclusion criteria.

III. Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Publication is written in English (Excluding Arctic Indigenous languages)	Publication written in other languages
Published in credible peer-reviewed journals	Non-Peer reviewed and unpublished thesis
Studies within the scope of this review. Directly address how regulation and management strategies have responded to reduce heavy metal pollution, specifically Mercury (Hg) and Lead (Pb)	Studies that are out of the scope of this review. Do not directly address how regulation and management strategies have responded to reduce heavy metal pollution, specifically Mercury (Hg) and Lead (Pb)
Contain data-driven analysis	Theoretical without empirical data
Published within the past 35 years (1988-2023) or cited for corroboration within the past 35 years	Publication outside the 35 years' timeframe or have not been corroborated within the past 35 years
Publication from Canada or dataset from Canada	Articles partnering with the Arctic but not addressing the research question or objectives
Scientifically backed adaptation measure	Primary focus on the whole Arctic and lack of possible extrapolation for the Canadian Arctic region

Qualitative, quantitative, and mixed-method methodologies	Duplicate studies
Controlled and uncontrolled experiments (Surveys, modelling studies, laboratory experiments, and ecological studies)	Opinion articles, editorials, and case reports

Table 1: Outlines the inclusion and exclusion criteria, which detail the characteristics of the sources that are eligible for inclusion in the study as well as those that are not. This was a crucial component of the primary and secondary screening of the sources, which are described in the following step.

IV. Primary and Secondary Screening: The PRISMA methodology employs a systematic two-step screening process to identify and select relevant articles and studies for inclusion in the literature review, ensuring alignment with the research questions and objectives[33]. Both primary and secondary screening processes were employed in this study.

In the primary screening stage, titles and abstracts of articles and studies were scanned to establish their relevance to the research questions and objectives. Articles not seen to have any established keywords in their title or abstract were excluded from further consideration. However, the articles and studies that met the screening threshold in the primary stage were further scrutinized in the secondary screening process. This involved roughly reading through the articles to determine if they meet the predefined inclusion and exclusion criteria and whether the insight provided has relevance to the research questions and objectives of this study. The articles, research, and datasets that successfully pass this step are preserved for the purpose of synthesizing findings and conducting analysis. Nevertheless, it is necessary to thoroughly evaluate the papers and studies to determine the validity of the results and the pertinence of the research questions.

V. **Result and research question relevance**: To meet the time constraints, avoid ambiguity, and ensure a clear interpretation of the extracted data, it was critical to include highly relevant materials that directly focus on climate change and its impact on the effectiveness of regulatory and management strategies to reduce heavy metal pollution in the Canadian arctic region, as well as potential adaptations that can be implemented to mitigate these impacts. This was done by organizing the extracted data in a tabular form and assessment based on the inclusion and exclusion criteria, considering the year of publication, study design, and critical findings[33]. Nevertheless, other results were used based on their feasibility to corroborate other studies based on commonalities and trends within its data, thus filling limitation gaps that would allow a conclusion to be drawn on the research question. After assessing the extracted data for relevance, it is analyzed to gain insights for conclusions and recommendations.

3.3 Data Analysis

Data analysis is interpreting and evaluating data based on well-defined variables by examining trends, patterns, and relationships[31]. In this study, thematic analysis was used because it was the most suitable for the systematic examination and interpretation of qualitative data from various sources, including climate measurements, mercury and lead deposit concentrations, observations, and cost-benefit analyses, providing valuable insights into the effectiveness of current regulations and management strategies in reducing heavy metal pollution in the Arctic region[31,32,33]. As with the PRISMA's systematic and rigorous approach, thematic analysis ensures that the data addresses the research questions and meets its objectives[34]. The data used for thematic analysis was majorly government data.

The government data utilized as a part of the qualitative data included reports, policy documents, official publications, and memos from government departments and subsidiaries involved in the Arctic and heavy metal regulation and monitoring. The Data from these governmental organizations was reviewed against one another for correlation and corroboration to identify trends, changes, and gaps within the various regulatory approaches. Moreover, additional data were obtained from peer-reviewed articles published in reputable journals, as described in the inclusion and exclusion criteria in step III of the search strategy. Similar to the data obtained from governmental organizations, these data were analyzed for similarities, corroborative findings, and inconsistencies through thematic analysis[31]. The data was systematically coded into themes and patterns around government reports, policies, and official documentation. To prevent repetitiveness, this method allowed the observation and presentation of existing patterns and frameworks that correlate the government's obtained data to peer-reviewed literature and provide insights on the cost and benefits of regulatory and management strategies utilized to manage heavy metals (Mercury (Hg) & Lead (Pb)) within the Arctic region[33].

Generally, the data analysis process relied directly on empirical data, legislative frameworks, and theoretical viewpoints to investigate the effectiveness of measures that would form a coherent insight and give evidential validity to these research findings and recommendations[33,34]. The results were discussed, and conclusions and recommendations were reached based on the insights from the analyzed data. However, as described in the following section, this study acknowledges that it was subject to some limitations and biases.

4 Results

4.1 Sources of Mercury and Lead Deposition and the Role of Climate Change

As stated in the research introduction, the Canadian Arctic has seen the deposition of heavy metals, including Mercury (Hg) and Lead (Pb), originating from both natural and anthropogenic sources[10].

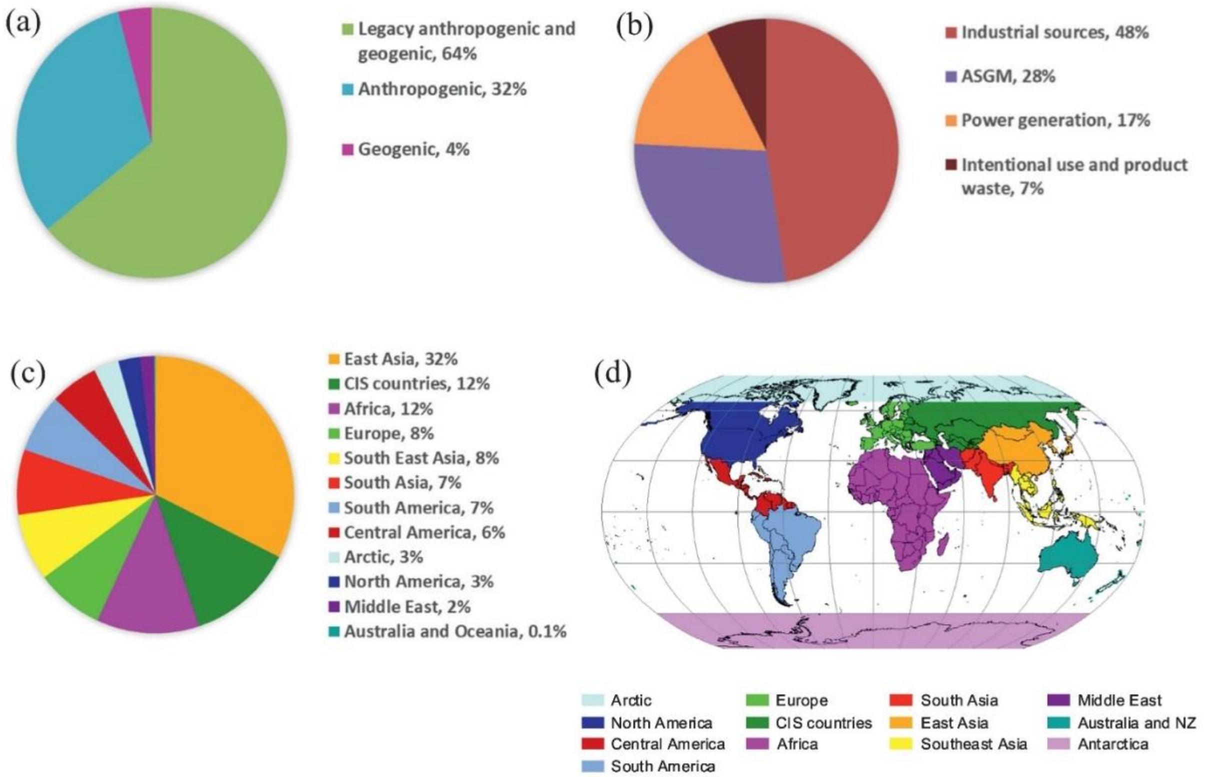

Figure 1: The relative contribution of the global anthropogenic Mercury emission and deposit sources. A.2015 Source of Mercury deposition. B. Sources regions. C. Anthropogenic Mercury deposit in the Arctic in 2015. D. Global sources by regions and continents. Source:(Dastoor et al., 2022)[10].

Figure 1 depicts the mining and manufacturing industries that contribute significant quantities of mercury and lead to the environment. The mode of transportation is a common denominator for the numerous anthropogenic sources highlighted in Figure 1. These sources are capable of being transported through atmospheric and oceanic pathways to the Arctic from long distances, such as Asia and Europe. This is important as it creates a containment and adaptation issue, as policies and management strategies would have to take this into account before implementation. Waste disposal, incineration, and fossil emissions of these heavy metals can make their way to the Arctic region and contribute to local contamination. Figure 1 highlights that mercury and lead deposition sources in the Canadian Arctic are interconnected; therefore, their impact would vary depending on proximity to pollution sources and prevailing wind patterns.

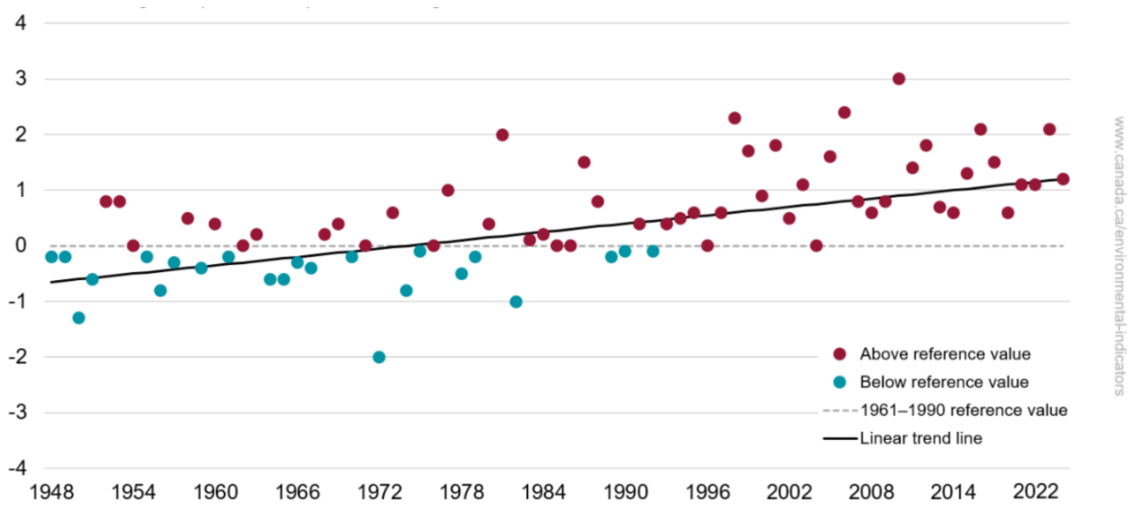

Figure 2: Average Annual temperature from 1948 to 2022 using reference values from 1961 to 199. Source: (Canada, 2016)[35]

Climate change is a significant contributor to the region's rise in heavy metal pollution[35]. With the increasing annual temperature of the Canadian region, Figure 2 shows an average temperature increase from 0.1°C to 3°C in 74 years of measurement[35]. Increasing temperatures have been noted to result in melting glaciers, sea ice, and permafrost, which can release previously trapped mercury and lead into the environment. This temperature change is also supported by Table 2, which is the global mean surface temperature (GMST) recorded in previous years of temperature and ocean level changes.

Year Range	Temperature	Range
1880 – 2012	0.85ºC (Rise)	Global Range
1971–2010	0.11ºC (Rise)	Ocean Level
1901–2010	0.19 Meters (Rise)	Ocean Level

Table 2: Temperature and Ocean Level rise. Source: (Bush & Lemmen, 2019)[36]

Furthermore, these instances show that the temperature increase has been beyond the normal levels of 0.1 degrees Celsius[35,36]. It is outlined that the Arctic Sea ice ocean's extent continues to decline every year from 1980 to 2020. This decline is at its highest peak during the summer when the temperature is at its recorded highest and slows during the winter period when the temperature drops[37].

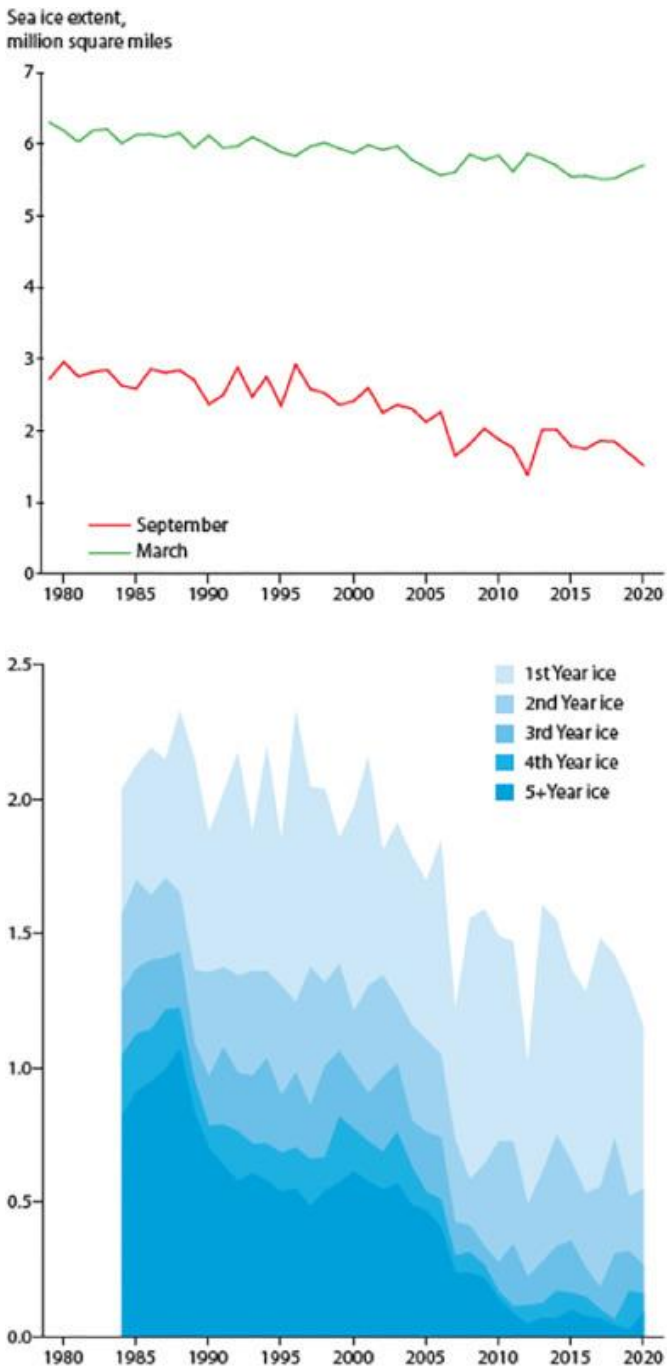

Figure 3: Sea ice extent decline in the Canadian Arctic Ocean over decades (Upper Image) and the Sea ice age change (Lower). Source: National Snow and Ice Data Centre;(Chételat et al., 2022)[37]

Figure 3 shows that Sea ice extends by 5.5 to 6.5 million square miles during the summer period due to high temperatures and reduces by 1.5 to 3.0 million square miles during the winter periods. This sea ice extent has negative implications for mercury and lead deposit in the Arctic as greater open water areas caused by extended sea ice may increase the flow of mercury and lead between the ocean and the atmosphere. Increased emission of these heavy metals from the ocean's surface is made possible by open water, which can be transported to and deposited in the Arctic region[37]. Figure 3 also shows the phenomenon known as Arctic amplification, which is assumed to be caused mainly by positive feedback with sea-ice melting, which reduces the snow caps and further increases the susceptibility of the region to heat. It further emphasizes that wide alterations to the atmosphere may have an impact on mercury (Hg) and lead (Ph) interaction with marine and terrestrial habitats as well as long-range transport to the Arctic.

Understanding the sources and cycle of Mercury and Lead deposition in the region provides a foundation for comprehending their concentration levels in sediment, ecosystem, and other organisms, including humans, within the context of the region.

4.2 Concentration of Mercury

The research conducted by Birgit Braune focused on the presence of Mercury in the Canadian Arctic area. Data was gathered from many environmental components, such as surface water, sediments, and biota[38]. The results from the analysis of these data indicate that mercury levels have been consistently elevated across different regions of the Canadian Arctic.

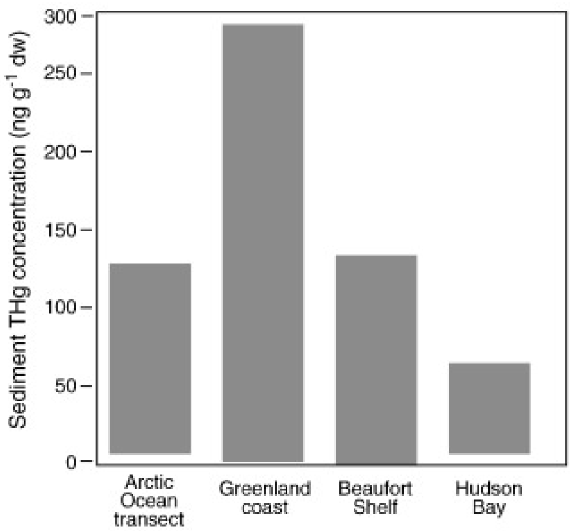

Figure 4: Mercury Reduction in previous years, Source:(Government of Canada, 2010) Ranges of sediment THg concentrations in marine regions in the circumpolar Arctic, specifically circumpolar Arctic, Beaufort Shelf, Greenland coast and Hudson Bay. Source: (Braune et al., 2015)[38]

In sediments, mercury levels ranged from 0.01 to 60 µg/g highlighted in Figure 5, with higher concentrations observed in areas impacted by industrial activities and an overall means concentration of 26 µg/g, which is higher than the probable effect level (PEL) set for mercury in sediment at 20 ng/g by the Canadian Council of Ministers of the Environment (CCME). Sediments act as a reservoir for accumulated contaminants over time, providing valuable insights into historical pollution levels and the long-term impact on the ecosystem thus, Whilst the concentration is on the low end above the recommended average, it still demonstrated that stable Hg concentrations existed in most cores at sediment depths accumulated before the industrial age. The data, as observed in Figure 4, is crucial because it gives an insight into the hotspot of mercury concentration and where the accumulation of mercury from various sources, including atmospheric deposition, runoff from surrounding areas, and local industrial activities, are at peak.

The research further highlights the impact of the transfer of mercury through different trophic levels and what this means for organisms within the ecosystem. Highlighted by the data from the research are bioaccumulation and biomagnification. Over the course of an organism's lifespan, bioaccumulation occurs, resulting in a larger concentration in people this would be organisms such as seabirds and seals and had a significant correlation to the percent of sea-ice cover as seen in Figure 3. In a food chain, biomagnification occurs when chemicals move from lower trophic levels to higher trophic levels, increasing the concentration of top predators. Biomagnification is found in marine waters at ultra-low levels, yet concentrations are orders of magnitude higher in predatory animals such as beluga and polar bears seen in Figure 5.

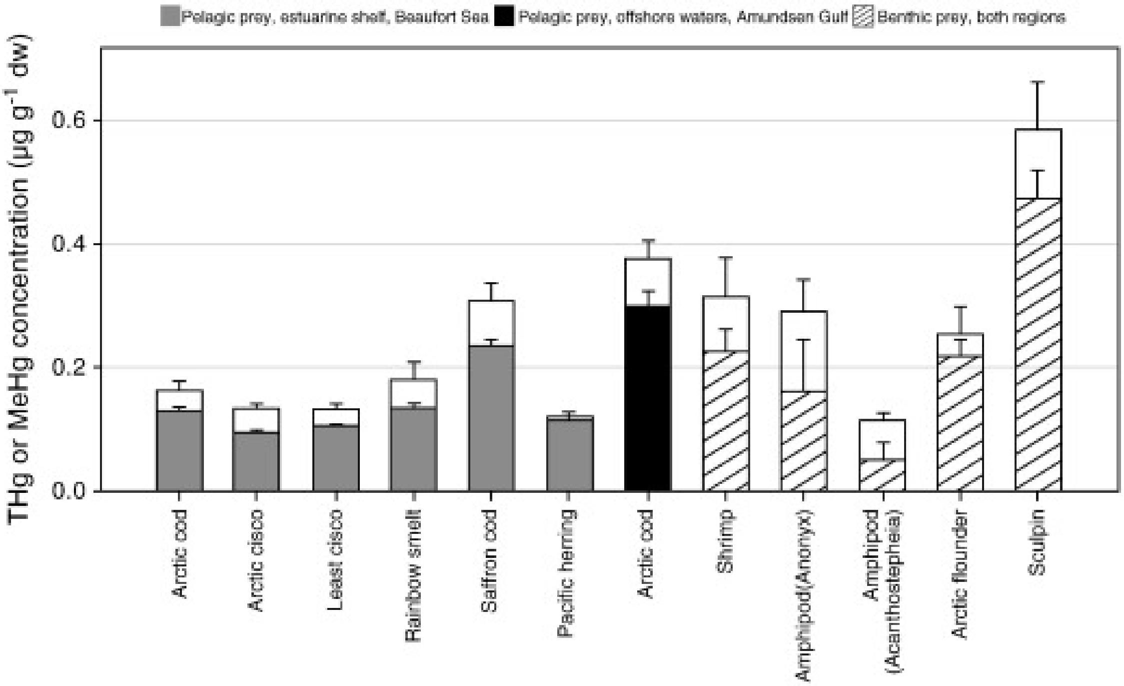

Figure 5: Concentrations of Total Mercury (Hg) (white and shaded) and Methyl Mercury (MeHg)(patterned bars) in potential prey species collected from different habitats of the Beaufort Sea and Amundsen Gulf. Source: (Braune et al., 2015)[38]

Mercury (Hg) is biomagnified through a food web, concentrates on microorganisms, and is amplified in dietary transfers. At the bottom of the food webs, Mercury (Hg) is approximately 105 times more concentrated in bacteria than in water, where the largest biomagnification is noted to occur[39]. Figure 4 shows the various Total Mercury (THg) concentrations in prey and the predator they feed. It gives an understanding of the trophic transfer of Hg in the different food webs. The variations in THg concentrations between beluga predators exploiting nearshore and offshore habitats were reported to be congruent with the differences in THg concentrations in prey, as seen in Figure 6. Beluga feeding at the ice edge and deeper offshore habitats, where THg concentrations were not significantly different, had higher THg concentrations than those feeding in the nearshore/shelf habitat, which had lower THg concentrations.

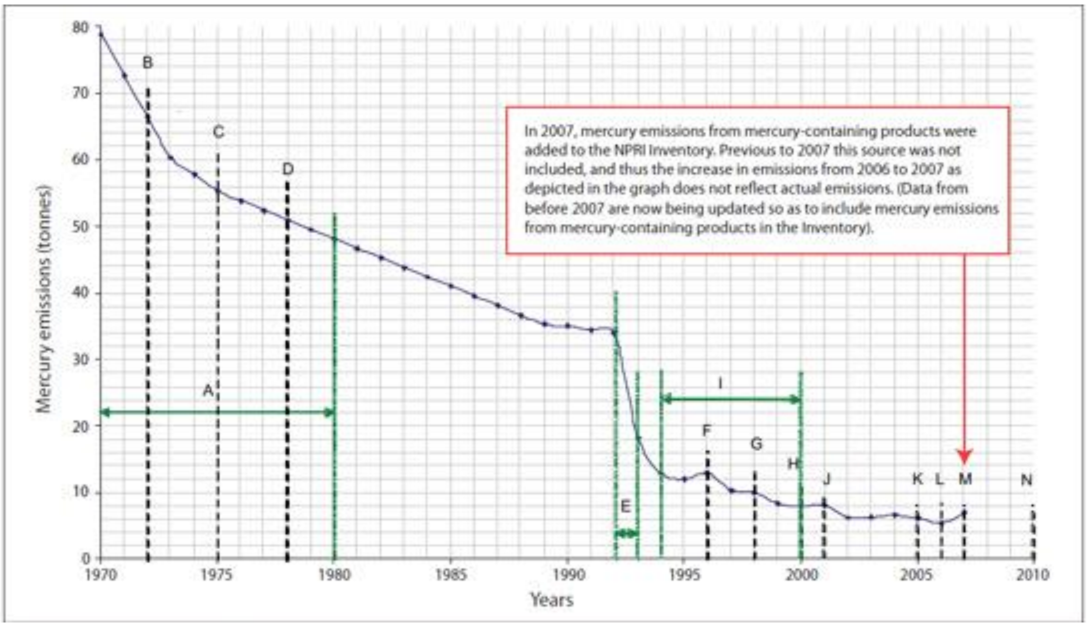

Figure 6: Mercury trend in Canada with initiatives introduced (the corresponding initiative letter is listed in Appendix A). Source:(Government of Canada, 2010)[40]

As was already indicated, the research's findings point to a possible influence of policy on mercury levels. Figure 6 shows how Canada successfully decreased emissions into the aquatic and atmospheric ecosystems through guidelines and measures. Canada's annual mercury emissions decreased from 34 tonnes in 1992 to ~18 tonnes in 1993[37]. This reduction can be attributed to various degrees of initiatives that were implemented provincially but federally[37]. The guidelines have reduced the usage of harmful metals, which further contributes to the reduction of temperature. While it is hard to determine the total effectiveness of the policy itself, the progress highlighted in Figure 6 is indicative of the need for Coalition on a global stage to handle Mercury deposition shown in Figure 1. If progress is to be made, action must be taken to manage the impending damages that would only get worse as more mercury and lead would be deposited from sea ice and permafrost due to the positive feedback loop due to climate change.

4.3 Lead Concentration

Lead concentration is highlighted in De Vera's research on Anthropogenic lead pervasive in Canadian Arctic seawater to have had an anthropogenic spread in the Canadian Arctic Ocean which increased from 5 p-moles/kg, to rising to 16 p-moles/kg from 1985-2015[41].

In addition, research sediment samples revealed elevated levels of lead, with concentrations ranging from 5.2 to 82.9 g/g, indicating the historical presence of lead in the region, with repercussions for the environmental and human health of the region's inhabitants. This concentration is noted to be varying due to the constant mixing that occurs with surrounding waters during its flow, as presented in Table 3[42,42].

Depth (m)	**CAA 1 (pmol kg-1)**	**Depth**	**CAA2**	**Depth**	**CAA3**
9.7	10.8	10.8	4.5	8.84	7.3
29.8	12.8	29.6	4.4	18.6	8.8
44	12.7	42.9	4.9	28.9	9.7
59.9	13.3	60.2	5.7	40. I	9
80.5	12.6	79.8	7.8	60.4	5.5
100.7	12.7	100.3	13.7	80.9	5.1
100.7	14.2	100.3	13.5	80.9	5.1
1212	7.1	121.2	9.1	101.3	4.1
150.6	5.1	150.2	10.3	120.4	3.8
201.3	5.8	201	4.1	150.9	3.2
300.7	5.7	301.5	5.1	200.4	4
402.4	32	403	4.7	301.4	7.8
603.5	4.6	603.2	4.9	402.1	5.3
603.5	4.8	603.2	5.1	402.1	5

Table 3: Lead Concentrations at various depths of the Canadian Arctic Region from The Canadian Arctic Archipelago (CAA) representing a transition environment influenced by Arctic waters imprinting a low-Pb signature. Source: (Rogalla et al., 2019)[42]

According to a study conducted by Peramaki in 2000, which focused on Lead in Soil and Sediment in Iqaluit, Nunavut, Canada, and its correlation with human health, it was found that the extent of lead poisoning in Iqaluit is comparatively less severe than the levels observed in numerous urban areas located in the southern regions of the country. The study further indicates that the majority of sites examined in Iqaluit do not present a significant risk to human health[43]. Therefore, it is not clear that lead in soil and sediment poses a major health risk. The study further highlights Lead levels in soil and sediment, which indicate the need for action but pose no imminent threat. It does a trend of increased soil-lead exposure, which does pose a risk, especially for children who require less exposure for their development[44].

Additional research conducted by Stalwick elucidated the significance of long-distance transportation from both the atmosphere and the ocean in the fluctuating levels of lead concentration observed in the Canadian Arctic and its subsequent bioaccumulation[45]. This bioaccumulation is seen by the research by Houde, which revealed that lead concentrations in liver and kidney tissues of ringed seals ranged from 0.02 to 1.14 µg/g wet weight, while polar bears exhibited lead concentrations ranging from 0.06 to 0.32 µg/g wet weight[6]. These findings are suggestive that lead bioaccumulation occurs in higher trophic level species in the Arctic food chain, as presented by the lead concentration in Figure 7, potentially posing risks to wildlife populations, the food web, and those who consume these animals as part of their traditional diets.

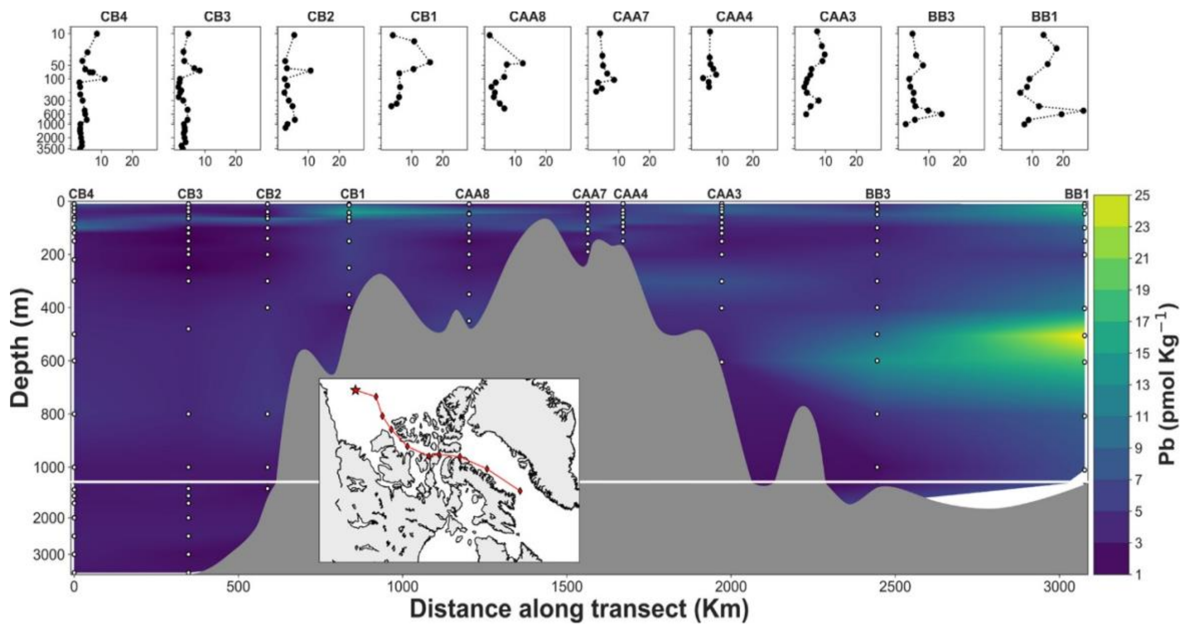

Figure 7: Contoured section of the dissolved Lead (Pb) concentration along the Canada Basin, the Canadian Arctic Archipelago, and the Baffin Bay. Source: (Rogalla et al., 2019)[42]

The elevated levels of lead in the Canadian Arctic area give rise to inquiries on the state of its infrastructure, ecological soundness, and the well-being of its population. The research exhibits a dearth of considerable information, hence limiting the capacity for an exhaustive examination of present levels. However, it does suggest the possibility of increasing levels in the future. The aforementioned factors can have adverse effects on the infrastructure, environment, and human health of the region. In terms of infrastructure, high lead concentrations in water sources lead to corrosion in pipes, releasing lead into drinking water supplies and creating health hazards that call for pricey remediation efforts. Other potential human health hazards are mainly to the Indigenous groups that rely on traditional subsistence hunting and fishing practices and may become exposed to Lead through consuming foods which have accumulated lead, such as aquatic organisms like fish and seals.

The research remains indicative of the need for further research to be carried out to fill knowledge gaps. It also highlights the limitation of policy and the need to tackle lead pollution from its Anthropogenic by incorporating regions and countries which are major contributors to the pollution to implement proper monitoring and remediation programs.

5 Discussion

5.1 Implication and Relevance of the Research

This research on the effectiveness of regulations and management measures on pollution from heavy metals in the Canadian Arctic has significant ramifications for Arctic communities, especially indigenous populations, and governmental policy on the region. The research offers policymakers valuable tools to make rational decisions about resource management, environmental regulations, and climate change adaptation plans by examining the efficacy of regulations and management strategies in reducing heavy metal pollution[46]. The results of this study can assist policymakers in better identifying and resolving the concerns raised by the effect of heavy metal pollution in the Arctic Region.

The finding of this research is particularly pertinent and significant for indigenous populations in the Arctic. Indigenous cultures are deeply rooted in the land, and the Arctic environment influences their way of life, cultural traditions, and sense of self. Thus, by promoting the adoption of effective laws and management strategies that lessen heavy metal pollution, the research findings will help safeguard and preserve indigenous populations[47]. Furthermore, this study emphasizes the necessity of incorporating the traditional knowledge and perspectives of indigenous populations into the development of policies. This approach will create more complete and culturally sensitive solutions that effectively address different indigenous communities' diverse needs and concerns. This research highlights the negative consequences of ignoring the heavy metal contamination in the Arctic. Heavy metal contamination endangers indigenous people's cultural and subsistence traditions in addition to endangering ecosystems, infrastructures, and human health. The risk of contaminating traditional food supplies is increased in the absence of suitable management plans and regulations, which can hurt indigenous diets and general health[48]. Additionally, the loss of cultural practices and traditions connected to the land might occur from environmental deterioration brought on by heavy metal pollution, further weakening the cultural foundation of indigenous groups and damaging critical infrastructures built to cater to the population's health and safety.

The literature review utilized during this research ensures that through the limitation gaps, policymakers and stakeholders have enough information to make decisions that conserve the environment, infrastructure, and the welfare of arctic communities. The results can help create and apply focused policies, rules, and management plans that address the problems caused by heavy metal contamination in the Canadian Arctic and further be extrapolated to other Arctic regions. In the end, this study aims to encourage resilience, save local customs, and support environmentally sound management techniques in the area.

5.2 Strengths and Limitations of the Research

The PRISMA research approach is a key strength in guaranteeing that the sources in the paper can respond to the research question[49]. The research methodology utilized a search approach using the keywords patterning to the research question to find pertinent academic papers, government reports, official records, and case studies. The trustworthiness and thoroughness of the literature study are increased by using various sources, including government and organizational-certified databases and credible search engines. The study reduces the chance of missing significant studies or data pertinent to the research topics by casting a wide net of inclusivity and using various sources, present and past, that have been peer-reviewed.

The inclusion of the critical appraisal process is another strength that allows the researcher to answer the research question. The research methodology thoroughly assessed the validity and dependability of chosen studies, articles, and datasets. The critical evaluation considered the study design, data collection method, target audience of the paper, and publication year[50]. The methodology's inclusion and exclusion criteria further strengthened this critical appraisal by providing precise specifications to guide the sources utilized in the selection process, ensuring that the studies chosen meets the study's aims and research concerns with limited bias.

Another advantage of the research methodology is the use of theme analysis as the data analysis strategy. Thematic analysis is ideally suited for methodically analyzing and understanding qualitative data from numerous sources, such as cost-benefit analyses, observations, mercury and lead deposit concentrations, and climatic measurements. Through this method, repeating themes, patterns, and linkages can be found that are pertinent to the success of the present rules and management plans in reducing heavy metal pollution in the Arctic. A strong framework for organizing and synthesizing qualitative data is provided by thematic analysis, allowing for the extraction of valuable insights from the data gathered. In conclusion, this study's research methodology has several advantages[51]. By having the analysis guided by PRISMA, the study can have an extensive and methodical methodology that has set defined parameter for its search strategy and concise inclusion and exclusion criteria that allows for the critical evaluation of information from sources utilized in the course of the paper to ensure the research’s reliability, transparency and rigor even with its limitation[33]. By utilizing these advantages, the research methodology guarantees a thorough review of the literature and produces insightful data on how well policies and management strategies affect heavy metal pollution in the Arctic.

To gain a thorough grasp of the study's breadth and ramifications, it is critical to recognize and resolve the research technique's limits, despite its varied merits. The following restrictions demand consideration:

A. Language Bias

Language bias is one major methodological drawback. The requirement that only works written in English be included may lead to the exclusion of studies or data published in other languages that could be useful. This linguistic bias could limit the review's thoroughness by omitting pertinent findings and viewpoints from non-English sources[48]. Future studies would have to consider utilizing translation services or working with academics who are bilingual in other languages to incorporate a broader range of literature to lessen this limitation.

B. Time Limitation

The time frame coverage of the source utilized in the research limits the knowledge utilized. The timeline presented in the research calls for publications for the last 35 years (1988–2023), disregarding prior case studies and research that were not peer-reviewed within those 35 years. While new studies can be included within this time range, earlier studies that provide substantial historical context or noteworthy conclusions may unintentionally be left out[52]. Historical research can shed light on long-term trends or modifications in heavy metal pollution and the efficacy of treatment techniques dating back more than 35 years. Future research might consider extending the timeline or including a historical analysis to better understand the historical contrariant of the region and the role heavy metals have played. In addition to the methodology time limit is the time constraint encountered for the completion of the project. It would be advisable for more comprehensive research to involve fieldwork in the Artic, including heavy metal sample collection and interviewing community members, especially indigenous elders, on their experience and knowledge dealing with the pollution.

C. Geographical Coverage Disparity

The presence of bias in the geographical coverage of the Canadian Arctic region, coupled with the need for a comprehensive and holistic approach to address the diverse and interconnected issues within the Arctic, underscores the necessity of acknowledging limitations and fostering flexibility in recommendations and solutions. This research methodology gives particular attention to Canadian Arctic and is more specific to Yukon and Nunavut. The generalizability of the results to other Arctic regions or settings may be constrained by this focus, even if it is pertinent to the research objectives and enables an in-depth analysis of the heavy metal pollution in these areas. Due to differences in the climate, culture, and governance structures, policies, and management techniques for minimizing heavy metal pollution may be less effective in some Arctic locations[53]. Given this restriction, future studies need to consider broadening the geographic focus to incorporate a wider variety of Arctic locales, such as Russia, Iceland, and the USA, to improve the generalizability of the results.

The reliability and relevance of findings can be increased by recognizing and resolving constraints and limitations. To get around these restrictions, future research might look into using techniques like translation services, alternative sources, the extension of the timeframe, or a wider geographic focus. This would provide a more thorough understanding of the impact of climate change on heavy metal pollution and the efficacy of rules and management techniques, not just in the Canadian Arctic but also in other locations confronting comparable difficulties[53]. Moreover, by comprehensively understanding these limitations, readers and stakeholders are more aptly prepared to evaluate the study's results with a discerning recognition of its restrictions and consequences. Despite these limitations, the research findings and solutions generated for the Canadian Arctic region contribute to our understanding and provide valuable insights that can inform future efforts toward comprehensive, long-term solutions for the Arctic. The limitation highlights the need for increased support and investment to facilitate long-term monitoring programs and interdisciplinary research initiatives. This would bridge the gaps in data availability and resource limitations, particularly the Inclusion of indigenous communities in the research process, including participatory approaches and the integration of traditional knowledge to provide a more holistic understanding of the impacts of heavy metal pollution on the Arctic environment and its indigenous inhabitants.

5.3 Future Research Directions

Several topics for additional research can be investigated to increase our knowledge of how a changing climate affects how well laws and management plans work to reduce heavy metal pollution in the Canadian Arctic. First, comparing the efficiency of rules and management practices across various Arctic regions would shed light on common ground of effectiveness and areas that require strengthening. Researchers can pinpoint the characteristics unique to each place and impact the effectiveness of pollution reduction initiatives by evaluating regions with various environmental conditions, governance frameworks, and cultural settings. Using a comparative approach, policymakers could better educate specific adaptations and develop measures tailored to certain Arctic locations.

The longitudinal studies represent still another field of investigation that should be explored. A more thorough understanding of patterns and variations over time would result from evaluating the long-term effects of climate change on heavy metal pollution and the efficacy of mitigating measures. To better comprehend the relationship between climate variability, levels of heavy metal pollution, and the effectiveness of current management strategies, longitudinal data can be used to clarify the cumulative effects of climate change[52]. Stakeholder viewpoints must be considered for a complete knowledge of heavy metal pollution in the Arctic. Speaking with representatives from the industry, policymakers, and indigenous groups could provide light on the problems, demands, and potential solutions relating to heavy metal pollution. These viewpoints can assist in creating and applying efficient rules and management techniques.

A mix of quantitative and qualitative data was considered to enhance the analysis. Integrating quantitative data, like pollution measurements and temperature data, with qualitative data from consumer interviews or surveys helps researchers clarify the complex linkages between heavy metal pollution, climate change, and mitigation initiatives. This integrated approach would provide a more sophisticated examination of the variables impacting pollution levels and the efficacy of management techniques[48]. The impact evaluation of adaptations should be the main topic of future research. It is crucial to identify potential adaptations, such as modifications to monitoring procedures or adopting new technology. However, assessing their viability and efficacy in actual situations is equally crucial. Case studies or scenario analyses would be used to evaluate the real-world effects of implementing adaptation methods. These studies would provide valuable data to stakeholders and policymakers, facilitating evidence-based decision-making and ensuring that modifications are feasible, sustainable, and effective in achieving the intended outcomes.

The transmission of knowledge and the ramifications for policy are crucial in bridging the divide between study and implementation. In order to maximize the practical implications of study outcomes, it is imperative to explore efficacious strategies for communicating research findings to lawmakers and stakeholders. Activities involving knowledge transfer or deliberate interaction with pertinent organizations and stakeholders can be included. Researchers may support decisions based on evidence and encourage the adoption of efficient laws and management techniques by actively distributing research findings and stimulating discussion[51]. Further study should include a socio-economic analysis to comprehend heavy metal pollution's economic and societal ramifications and mitigation measures. A comprehensive understanding of what this means for pollution reduction initiatives can be achieved by comparing the costs and benefits of various management strategies, assessing potential trade-offs, and discovering co-benefits. Moreover, it is essential to promote coordinated research activities to tackle the intricate problems caused by heavy metal contamination in the Arctic. Knowledge exchange, data access, and the co-creation of solutions can be made easier by collaboration between academic institutions, governmental organizations, indigenous communities, and industry stakeholders. Researchers can use various views, resources, and expertise to provide comprehensive and context-specific approaches to pollution reduction by promoting multidisciplinary cooperation[50]. Collaboration in research can strengthen local community capability and encourage community involvement in monitoring and management programs.

The application and influence of the study on the efficiency of policies and management plans in decreasing heavy metal pollution in the Canadian Arctic under changing climatic circumstances can be improved by following these research lines. These study directions would advance our knowledge of the intricate relationships between heavy metal pollution, climate change, and mitigation strategies, ultimately guiding evidence-based decision-making and encouraging sustainable environmental management methods in the Arctic.

6 Conclusion

In conclusion, this paper has highlighted a comprehensive assessment of heavy metal pollution, specifically Mercury (Hg) and Lead (Pb), in the Artic and further evaluated how current regulations and management policies have been effective towards managing the pollution. Through an in-depth analysis, the research examined policies such as Mercury (Hg) and Air Toxics Standards (MATS) which is a cooperation between Canada and the United States of America to lower mercury (Hg) and other dangerous air pollutants, Northern Toxins Program (NCP), a comprehensive project to monitor and reduce toxins in the Canadian Arctic, Canadian Arctic Contaminants Assessment Report (CACAR) which has been an evaluation tool for monitoring heavy metal levels, distribution and spread of its pollution in the arctic and nearby regions and the Arctic and Northern Policy Framework (ANPF) which directs the administration and oversight of the Canadian Arctic region assessing heavy metal pollution impacts and mitigative and adaptive efforts.

This study examined the complex correlation between climatic change and the extent of heavy metal contamination in the local area. This study investigated the potential impact of metals on the exacerbation of climate change in the area, with particular emphasis on their accumulation in permafrost and glaciers. Doing so aimed to enhance our understanding of the imminent risks posed to ecosystems, infrastructure, human well-being, and cultural traditions. The research also highlighted various limitations and gaps in the current measures to address heavy metal pollution in the Arctic and the knowledge available to understand the damage due to the pollution in the region. This limitation paves the way for investment by stakeholders and government bodies in potential adaptation and policy changes that will enhance the current approach and increase the efficacy of existing strategies.

Moving forward, this research will encourage future collaborations with the local and indigenous communities to develop community-targeted policies for development, adaptation and minimize the negative impacts of heavy metal pollution in the region. Bridging this knowledge gap would be essential in ensuring that tangible actions and effective measures are scientifically supported along with indigenous wisdom of traditional ecology in policy-making processes, ensuring the preservation of indigenous communities' cultural practices and way of life.

Although this research represents a significant step forward, more research is still needed. This study emphasizes the importance of long-term, focused monitoring of heavy metal pollution to evaluate its effects on the environment and people now and to develop defences against further contamination from other sources in the future. Additionally, it outlines responsibilities for private parties to develop mitigating measures that can close the gap and lead to the discovery of a long-lasting solution that safeguards the area and its residents. According to William Butler Yeats, a 20th-century writer and poet, “The world is full of magic things, patiently waiting for our senses to grow sharper”[54]. The potential of the Arctic can be unleashed, and the region can be made sustainable and thriving for current and future generations by consistently improving our understanding, working across disciplines and cultural beliefs, and adopting wise, decisive action.

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Appendix

Appendix A: Figure 6 Continued: Summary of initiatives introduced that contributed to the Canadian Emission Trend.

A

1970-1980: Closure of 10 of 15 mercury cell chlor-alkali facilities

B

1972: Alkali Mercury Liquid Effluent Regulations (Fisheries Act)

C

1975: Closure of the Pinchi Lake primary mercury mine in 1975

D

1978: Chlor-Alkali Mercury National Emissions Standards Regulations (Clean Air Act)

E

1992–1993: Process change by the Hudson Bay Mining & Smelting Co. facility in Flin Flon, Manitoba

F

1996: National Guidelines for the Use of Hazardous and Non-Hazardous Wastes as Supplementary Fuels in Cement Kilns

G

1998: National Emission Guideline for Cement Kilns 1998: Mercury-based pesticide active ingredients no longer registered for use

H

2000: Canada-wide Standards for Mercury Emissions from Incineration and Base Metal Smelting

I

1994–2000: Accelerated Reduction/Elimination of Toxics program

J

2001: Environmental Code of Practice for Integrated Steel Mills and Environmental Code of Practice for Non-Integrated Steel Mills 2001: Canada-wide Standard for Mercury-Containing Lamps 2001: Canada-wide Standard on Mercury for Dental Amalgam Waste

K

2005: Surface Coating Materials Regulations (Hazardous Products Act)

L

2006: Canada-wide Standards for Mercury Emissions from Coal-Fired Electric Power Generation Plants
2006: Environmental Code of Practice for Base Metals Smelters and Refineries
2006: Notice requiring the preparation and implementation of pollution prevention plans in respect of specified toxic substances released from base metals smelters and refineries and zinc plants
2006: Cosmetic Ingredient Hotlist (2006) of the Cosmetic Regulations under the Food and Drugs Act

M

2007: Notice requiring the preparation and implementation of pollution prevention plans in respect of mercury releases from mercury switches in end-of-life vehicles processed by steel mills

N

2010: Notice Requiring the Preparation and Implementation of Pollution Prevention Plans in Respect of Mercury Releases from Dental Amalgam Waste