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Heavy Metal Contamination and Breast Cancer Risk in Women of South Asia: An Urgent Environmental Health Concern

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Abstract

Breast cancer is one of the most prevalent cancers among women worldwide and poses a growing threat in South Asia, particularly in countries like India, Pakistan, and Bangladesh. This review highlights heavy metal contamination as a potentially significant material that is an overlooked risk factor in breast carcinogenesis, outlines mechanistic insights into their biological effects, and advocates for region-specific research and policy intervention. The risk of breast cancer in women is also linked with genetic, hormonal, and lifestyle factors. However, the role of environmental contaminants, particularly toxic heavy metals, like Arsenic (As), Cadmium (Cd), Lead (Pb), Chromium (Cr), Mercury (Hg), and Nickel (Ni), can not be ignored because of their untreated discharges in agriculture and land soil, specifically in the India, Pakistan, and Bangladesh is a common experience. These metals, primarily released through industrial emissions, agricultural runoff, and urban pollution, exhibit carcinogenic properties through mechanisms including oxidative stress, endocrine disruption, and DNA damage. The persistence of heavy metals in soil, water, and food chains, especially rice and vegetables, elevates chronic exposure risks among South Asian women, who often live in proximity to polluted environments and consume locally grown produce. Case studies in cancer from these regions' focus areas, such as the Malwa region in India and industrial zones in Bangladesh, further support the association between heavy metal contamination and elevated breast cancer risks in women of these regions. An effort has been made in the present review to merge current evidence on heavy metal-induced carcinogenesis, highlight exposure pathways unique to South Asia, and discuss emerging mitigation strategies, including bioremediation, regulatory enforcement, and public health interventions.

Keywords: Breast Cancer, women, South Asia, Heavy metal, urban contamination

1. INTRODUCTION

The most common cancer in women worldwide is Breast cancer. This is the most prevalent cancer and the second leading cause of death among women in Asia. Accounting for 39% of global cases, its rising mortality rate strains healthcare systems and diminishes patients' quality of life. In 2012, breast cancer accounted for 40.8% of all female cancer-related deaths in Asia, ranking second only to lung cancer and emphasizing its status as a critical public health concern. Despite an age-standardized mortality rate (10.2 per 100,000) lower than the global average (12.9 per 100,000), Asia's rate aligns with countries classified as having a medium Human Development Index.[1]. The female population (84.1 million) exceeds the male population (79.5 million), including 45 million women in their reproductive years and 13.5 million aged 50 and above [2].

In Pakistan, the incidence of female breast cancer was reported to be 50.1 per 100,000, making it the most common malignancy in Pakistani women [3]. According to Globocan 2020 data, breast cancer represented 13.5% (178,361 cases) of all cancer cases and 10.6% (90,408 deaths) of all cancer-related deaths in India, with a cumulative risk of 2.81 [4]. Furthermore, the role of toxic heavy metals originating primarily from industrial and agricultural activities is gaining recognition as a significant yet often overlooked carcinogenic threat. With a particular focus on pollution in Pakistan, India, and Bangladesh, this article examines the regional burden of breast cancer through the lens of heavy metal exposure, their environmental persistence, and the unique susceptibility pathways in South Asian populations. This review article also explores epidemiology, regional trends, genetic and lifestyle factors causing Breast Cancer. In addition, it highlights breast cancer as an escalating public health challenge in South Asia, where its rising prevalence is influenced by a multifaceted combination of genetic predisposition, lifestyle choices, and, notably, environmental exposures.

2.1. Metals: Chemical Properties and Environmental Persistence

Heavy metals like As, Cd, and Hg persist indefinitely in ecosystems due to their non-biodegradable nature, meaning natural processes cannot break them down, accumulating in living organisms and potentially causing harm when entering human food chains through contaminated soil and water, followed by contributing to elevated cancer risks across South Asia through chronic exposure. Methylmercury, the highly toxic organic form of mercury, bioaccumulates persistently in aquatic food chains, particularly in fish, creating long-term carcinogenic risks for populations with high seafood consumption. Cd is a toxic environmental pollutant that accumulates in kidneys, disrupts endocrine function, and is classified as carcinogenic, with chronic exposure linked to Itai-Itai disease and potential cancer risks [5]. As it accumulates in human tissues, with its high density and metalloid properties, it induces oxidative DNA damage and genomic instability, mechanisms implicated in various cancers, including potential breast malignancies [6,7].

2.1. Industrial /Urban Emissions and Rice Crop

South Asia's tanneries (Cr/Cd), battery recycling (Cd/Pb), and metal smelting (Pb/Cu/Zn) create a toxic urban waste, followed by Dhaka/Delhi dust showing 200× above normal levels. These endocrine-disrupting metals directly increase breast cancer risks through chronic exposure. Urgent industrial controls and biomonitoring are needed to protect exposed populations [8]. In South Asia, industrial emissions and urban traffic are major contributors to heavy metal contamination, as seen in Multan, where elevated levels of As, Pb, and Zn in street dust originate from fossil fuel combustion and vehicular activities (Fig.1). These pollutants pose health risks through oral exposure, particularly in densely populated areas [8].

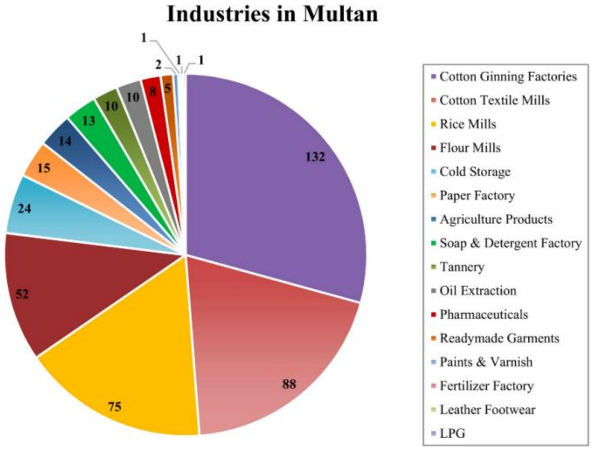

Figure 1: Sourced from Punjab Government. [10]

Groundwater near industrial hubs in northern India shows elevated levels of heavy metals like As, Pb, and Al, primarily due to industrial discharge, agricultural runoff, and waste dumping. These metals (loid)s, exceeding the Bureau of Indian Standards (BIS) and the World Health Organization (WHO) limits, pose significant non-carcinogenic and carcinogenic health risks through contaminated drinking water [9]. In South Asia, industrial emissions (e.g., tanneries), vehicular traffic, and agricultural practices involving pesticides are major pathways of heavy metal contamination in air, water, and soil. This leads to the accumulation of toxic metals like Pb, Ni, and Cd, particularly in urban street dust, posing significant health risks and increasing the prevalence of chronic diseases, including cancer, in densely populated areas.[10- 12].

Heavy metals negatively impact soil microorganisms, affecting soil fertility and ecosystem function. Their accumulation in soils, particularly As, Cd, and Cu, is associated mainly with fertilizer and compost use. Elevated concentrations of these metals were also found in food crops like rice, groundnut, especially brown rice, and mustard, which tend to accumulate more than other grains. Long-term consumption of rice with high levels of these metals can lead to health issues, including cancer and developmental problems, highlighting dietary exposure risks. Diffuse sources, such as atmospheric deposition, have been identified as primary contributors to mercury (Hg) contamination.

In contrast, background soil mineralogy plays a significant role in influencing cobalt (Co), nickel (Ni), and zinc (Zn) concentrations [13] (Fig.1). In Asia, home to more than 90% of global rice production, paddy fields are increasingly impacted by heavy metal contamination arising from agrochemical application, irrigation with untreated or partially treated wastewater, and long-range atmospheric transport. Toxic metals, including Cadmium (Cd), lead (Pb), Arsenic (As), and chromium (Cr), can accumulate in various parts of the rice plant, with foliar uptake being particularly obvious in fields located near highways. While concentrations of heavy metals in rice grains often remain below internationally recognized safety thresholds. Chronic dietary exposure poses a significant public health risk, especially given the well-documented carcinogenic potential of Cd and As. These findings emphasize the urgency of continued environmental monitoring and the implementation of effective soil remediation strategies across South Asia [14].

2.2. Heavy Metals as Emerging Carcinogens

Asia exhibits the highest average concentrations of metals in road dust, followed by the Americas, Europe, and Australia, while cities in Africa report the lowest levels. Ingestion represents the primary pathway of human exposure, with children in Asia being particularly susceptible to the non-carcinogenic health effects of lead (Pb) due to frequent hand-to-mouth behavior, higher dust ingestion rates per body weight, and underdeveloped detoxification systems. Although inhalation generally poses minimal risk and most metals remain within established carcinogenic thresholds, Cadmium (Cd) and lead (Pb) continue to represent the most significant ecological and public health concerns in the region. Limited data from the under-researched areas presents a critical knowledge gap, especially given rising urban emissions and potential links to chronic diseases such as cancer [14]. The suburban industrial area of Gazipur, Bangladesh, which is part of the Dhaka-Gazipur terrace, is a location of significant urban and industrial development [15]. The Dhaka-Gazipur Terrace is part of the Madhupur Tract, located in the central region of Bangladesh. In the longitude and latitude system, the coordinates can be located at 25°15′0″ N, 89°30′0″ E (or 25.25° N, 89.5° E in the decimal format). This specific area is positioned as a tectonically active region within the Bengal Basin, which has folded and tilted mountains in its vicinity. The Tanaka Gazi dip terraces, as well as the skirts, stand moderately above the surrounding floodplains. The Tanaka Gazi dip terrace is slightly higher than the hilly rivers of Buriganga and Turag, which are positioned in the western region, while the Balu is in the eastern region. The region is composed of Madhapur Clay, which is formed at a higher elevation and is not subject to weather systems, which significantly facilitates the expansion of its urban and industrial centers, especially in Dhaka and Gazipur. A map of the sub-urban Gazipur industrial area of Bangladesh (Fig. 3) while Figure 2 also represents a high level of heavy metals, such as Arsenic, Cadmium, and lead, in vegetables and fruits [15].

The soil in this area has shown a wide variation in heavy metal concentrations, with iron (Fe) having the highest average concentration at 23,474.75 mg/kg, and Cd the lowest at 0.32 mg/kg. Compared to background levels, the carcinogenic heavy metal content in this soil has increased about two-fold, likely due to the frequent use of industrial wastewater for irrigation and the excessive application of metal-based fertilizers and pesticides. The soil has been identified as moderately polluted by several metals, including manganese (Mn), vanadium (V), Ni, Zn, and Cu, with Mn being considered a potential toxicant. Heavy metals such as Cadmium (Cd), Arsenic (As), and lead (Pb), commonly found Vegetables and fruits cultivated near suburban industrial areas of Bangladesh present significant carcinogenic risks, primarily via dietary exposure. Cadmium showed the highest cancer risk, highlighting the role of contaminated food as a critical exposure route for emerging metal-based carcinogens [16-18]. Heavy metals are transitioning from mere environmental pollutants to recognized carcinogens, posing significant risks to human health. A study on the Damodar River in India revealed that high concentrations of heavy metals like Cadmium (Cd) and Chromium (Cr) in water and sediment pose significant carcinogenic and non-carcinogenic risks, particularly to children. The study found that exposure through sediment was a much greater risk of cancer than through water, with children being more susceptible due to their distinct physiological and behavioral characteristics. The presence of these metals, primarily linked to industrial and mining activities, can lead to severe health issues, including various cancers, as they accumulate in human body tissues through ingestion and dermal contact. This threat required the urgent need for remediation and policymaking to manage these health risks and prevent the further transition of environmental pollutants into life-threatening human carcinogens, like those associated with breast cancer [18].

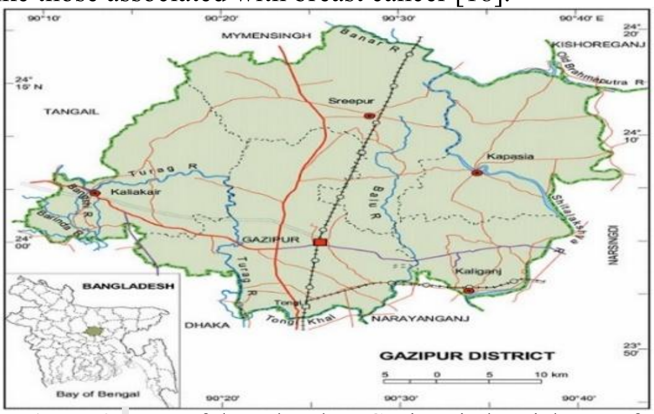

Figure 2: Map of the sub-urban Gazipur industrial area of Bangladesh. [16]

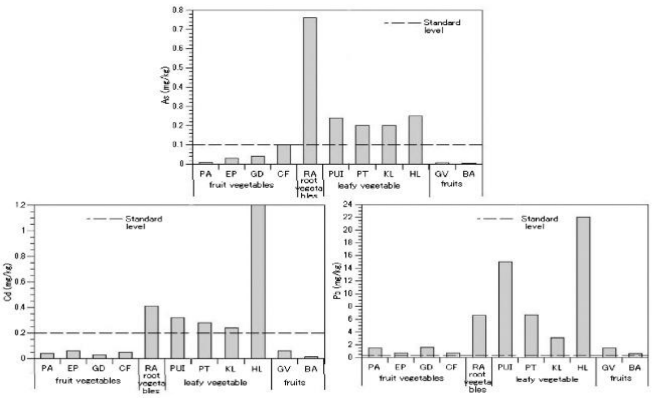

Figure 3: Carcinogenic heavy metals in the studied vegetables and fruits. [16]

2.3. Mechanisms of Carcinogenesis

The human body has been linked to heavy metals, such as estrogen, which could upset the endocrine system and impair general health. These metals tend to accumulate in the human body, and they are not recognized by the human body, which creates further problems, such as disrupting normal bodily functions, as the human body cannot neutralize or excrete them normally. This problematic way of persistence of metals in the human body increases the chance of the occurrence of diseases like breast cancer. Exposure to heavy metals in the human body can cause oxidative stress and inflammation, which further impair cellular functions and interfere with metabolism [19]. Heavy metals affect breast cancer through DNA damage and oxidative stress. This DNA damage destroys signalling pathways that can further lead to cellular changes such as Epithelial-Mesenchymal Transition (EMT). These processes ultimately become the reason for the development and propagation of cancerous cells [20]. Cadmium (Cd), a toxic heavy metal and potent endocrine disruptor, exhibits estrogen-like activity by interacting with estrogen receptor alpha (ERα), thereby mimicking the hormonal effects of estradiol in breast tissue. Studies have shown that Cd enhances the proliferation of MCF-7 breast cancer cells through ERα-mediated activation of signalling pathways such as Akt, ERK1/2, and PDGFRα [21]. The use of ER antagonists like ICI 182,780 significantly reduces these effects, confirming the receptor-dependent mechanism. Moreover, Cd stimulates the expression of key proto-oncogenes, including c-fos, c-jun, and PDGFA, which are associated with tumor development. These findings indicate that Cd contributes to breast carcinogenesis through both non-genomic signaling and gene regulation, highlighting its role in disrupting cellular homeostasis and promoting malignant transformation [21-25]. Oxidative stress plays a central role in metal-induced carcinogenesis. Many heavy metals, including cadmium, iron, copper, and chromium, can generate reactive oxygen species (ROS) either directly or by disrupting the cellular redox balance. These ROS, such as superoxide anions, hydroxyl radicals, and hydrogen peroxide, can cause significant cellular damage by attacking DNA, lipids, and proteins (Fig.4). In particular, DNA damage induced by ROS may result in mutations if not correctly repaired, potentially initiating tumorigenesis [21]. Moreover, oxidative stress can interfere with DNA repair enzymes and activate signaling pathways like NF-κB and AP-1, which regulate genes involved in inflammation, cell survival, and proliferation. When antioxidant defenses such as glutathione are overwhelmed, cells become more susceptible to oxidative damage, thereby increasing the risk of malignant transformation [21-28].

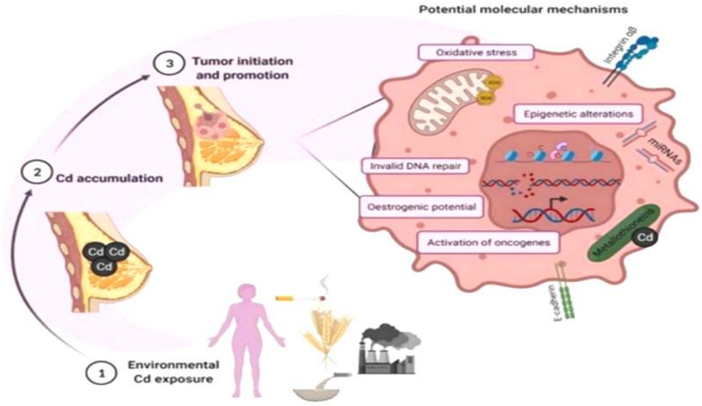

Figure 4: Tarhonska *et al.* proposed a possible mechanism of Cd toxicity [24]

2.4. South Asian Exposure Pathways and Vulnerabilities

Heavy metal exposure has emerged as a significant environmental and public health concern in South Asian countries, where millions of women are chronically exposed to toxic metals such as Arsenic (As), Cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni). The primary exposure pathways in this region include ingestion of contaminated groundwater, consumption of polluted food (mainly rice and vegetables), and inhalation of metal-laden dust from industrial and vehicular sources. These pathways are not only geographically widespread but are also intensified by regional socio-economic and infrastructural vulnerabilities. In the Malwa region of Punjab, India, a recognized cancer trouble spot, a case-control study evaluated the concentrations of heavy metals in breast tissue and found significantly elevated levels of Cd, Cr, Ni, and Pb in malignant tumor samples compared to benign and control tissues [22-23].

This biomonitoring evidence suggests that these metals possibly play a role in breast cancer in women, followed by the disturbance in the overall body function, which may contribute to the initiation and progression of breast cancer. Notably, the study also highlighted occupational and environmental sources of exposure, including proximity to agricultural land using chemical fertilizers and industrial discharges. Arsenic-contaminated groundwater remains one of the most prominent and persistent sources of exposure in South Asia. Bangladesh alone has over 57 million people consuming drinking water with Arsenic (As) concentrations above the WHO-recommended limits [24-29].In Pakistan, especially in rural areas of Punjab and Sindh, studies have reported arsenic concentrations exceeding 50 µg/L in groundwater, disproportionately affecting women who are traditionally responsible for collecting water and cooking [24]. Chronic ingestion of Arsenic not only increases risks of skin and liver cancer but is also increasingly being implicated in hormone-sensitive cancers such as breast malignancies, due to its ability to disrupt estrogen receptor signaling.

In addition to water, food grown with arsenic or cadmium-contaminated irrigation sources represents another potent exposure route. A regional analysis of rice grown in arsenic-rich soil in Bangladesh and West Bengal revealed significantly elevated As accumulation in the edible portions of crops, which are dietary staples for millions of women [24]. Similarly, vegetables irrigated with wastewater in peri-urban regions of Lahore and Peshawar have shown toxic levels of Pb and Cd, two well-established carcinogens, thereby increasing the risk of long-term dietary exposure among female populations. These findings underline a convergence of environmental toxicity and dietary vulnerability, rendering South Asian women particularly susceptible to heavy metal-induced carcinogenesis. Human exposure to heavy metals through different routes is reported in Table.

Table 1: Heavy Metal Exposure Pathways & Health Risks in South Asia

Exposure Route	Primary Sources	Affected Regions	Key Metals	Health Risks
Ingestion (Water/Food)	Contaminated groundwater, rice, and vegetables	Bangladesh (As), Punjab (Cd), West Bengal (As)	As, Cd, Pb	Breast cancer, kidney/liver damage
Inhalation (Air/Dust)	Industrial emissions, vehicular exhaust	Delhi, Dhaka, Lahore	Pb, Ni, Cd	Lung disease, DNA damage
Dermal Contact	Polluted soil, industrial wastewater	Tanneries (Bangladesh/India), mining zones	Cr, Hg	Skin lesions, carcinogenic

2.5. Mitigation Strategies and Policy Recommendations

To address the rising concern of heavy metal exposure and its possible role in breast cancer among women in South Asia, a combination of regulatory enforcement, environmental cleanup, and public health initiatives is required. Industrial pollution remains a primary contributor to heavy metal contamination in the region, particularly in rapidly growing urban centers. In Punjab, India, the state pollution board has recently issued final warnings to Ludhiana's dyeing units to adopt zero-liquid-discharge (ZLD) technologies or shift operations outside city limits. This action is part of efforts to prevent further contamination of water bodies like Buddha Nullah, which are known to carry high levels of Chromium, Cadmium, and other toxic metals [29]. Such interventions emphasize the importance of strong institutional enforcement to prevent industrial discharge from reaching agricultural and residential zones, where exposure risks are highest for women and children.

To minimize heavy metals in the environment, there are different techniques, such as bioremediation and phytoremediation, which have gained momentum as practical and eco-friendly tools for reducing heavy metals from the environment. In Lakki Marwat, Pakistan, researchers tested several species of mustard (*Brassica juncea*) for their ability to absorb cadmium and lead from contaminated soils. Results showed that *B. juncea* had a particularly high accumulation potential, making it suitable for cleaning metal-laden agricultural land before food crops are planted [24-30]. Similarly, in Dargai, Khyber Pakhtunkhwa, native plants like *Pteris vittata* and *Ricinus communis* were used to absorb heavy metals from soil and wastewater near steel mills. These phytoremediation trials revealed measurable decreases in metal levels, suggesting their potential for broader field-scale application [28].

For urban waterway restoration, microbial bioremediation is being employed as a low-cost strategy to degrade pollutants. In Ghaziabad, India, local authorities collaborated with scientists from IIT to introduce beneficial bacteria into major drains that flow into the Yamuna River. These bacteria helped improve water quality by reducing heavy metal concentrations and improving oxygenation levels, demonstrating how biological methods can complement engineering solutions in densely populated cities [27].

However, these technologies can only be successful when backed by effective environmental laws and long-term political commitment. Bangladesh's Environment Conservation Act of 1995 and India's Environment (Protection) Act of 1986 offer regulatory frameworks for pollution control, yet enforcement is often inconsistent and reactive. The Bangladeshi law, for example, focuses more on post-violation penalties rather than preventive measures, while India's central law suffers from poor local implementation and limited monitoring capacity [28].

In parallel with regulatory efforts, public awareness and policy integration remain key. Many women in South Asia, particularly those in rural or industrial-adjacent communities, are unaware of the cancer risks associated with heavy metal exposure. Education campaigns, community health outreach, and the integration of environmental screening into national cancer prevention programs could help bridge this gap. Additionally, collecting data on metal levels in blood, tissue, or water used by breast cancer patients would help identify high-risk areas and populations, guiding future interventions.

Altogether, these strategies show that reducing breast cancer risk from environmental heavy metals in South Asia is not only a scientific challenge but also a social and governance issue [25-30]. To minimize heavy metals in the environment, different techniques such as bioremediation and phytoremediation, which have gained momentum as practical and eco-friendly tools for reducing heavy metals from the environment, must be adopted for women's safety. Through strengthened environmental laws, investment in low-cost remediation technologies, and grassroots-level awareness, governments and communities can work together to create safer, healthier environments for women.

CONCLUSION

The rising incidence of breast cancer in South Asia is intricately associated with chronic exposure to carcinogenic heavy metals, a consequence of rapid industrialization, inadequate environmental regulations, and socio-economic exposures. Although the toxicological roles of metals such as Cadmium, Arsenic, and lead in breast cancer pathogenesis remain under investigation, accumulating evidence from biomonitoring and environmental studies highlights a troubling pattern of environmental injustice, disproportionately impacting women in low-income and peri-urban communities. The persistence of these metals in air, soil, food, and groundwater highlights the need for urgent intervention. Sustainable mitigation approaches, including zero-liquid discharge technologies, phytoremediation, and microbial bioremediation, must be integrated with robust policy frameworks and targeted community education to minimize exposure and prevent disease onset. Addressing heavy metal contamination as both a public health and environmental crisis is imperative for the formulation of comprehensive cancer prevention strategies in South Asia.

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