Cancer control in Mongolia: Air pollution and molecular insights from hepatocellular carcinoma

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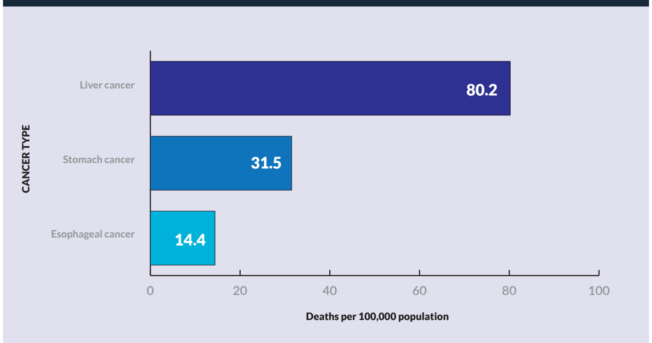
Despite its beautiful landscapes and warm-hearted people, Mongolia unfortunately has one of the highest cancer mortality rates in the world, with hepatocellular carcinoma (HCC) being a major contributor. While viral hepatitis remains a major etiological factor, emerging molecular evidence suggests that environmental exposures, including air pollution, may also play a significant role in carcinogenesis. Recent genomic analyses of Mongolian HCC reveal distinct mutational signatures associated with environmental carcinogens, suggesting a broader environmental contribution to cancer risk beyond traditional factors. This article synthesizes epidemiological, environmental, and molecular evidence to examine the intersection between air pollution and cancer in Mongolia, with particular emphasis on urban exposure in Ulaanbaatar. It further discusses structural challenges in cancer control and identifies opportunities for integrating air quality interventions into national prevention strategies. Addressing environmental determinants represents a critical opportunity to reduce the cancer burden in Mongolia.

Cancer control in Mongolia presents a uniquely complex challenge shaped by infectious, behavioral, and environmental determinants. The country reports exceptionally high incidence and mortality rates for liver and stomach cancer, largely attributed to chronic infections with hepatitis B virus (HBV), hepatitis C virus (HCV), and Helicobacter pylori, together with high rates of alcohol consumption and tobacco use. However, this traditional explanation is increasingly insufficient.

Table 1: Mortality rates by specific cancer site



Epidemiological pattern of cancer in Mongolia

Cancer distribution patterns in Mongolia show a persistently high burden of liver and stomach cancers in both men and women, with substantially higher proportions observed among males. As of 2025, liver cancer remains the leading malignancy in both sexes, accounting for 29.2% of cancers in males and 24.7% in females, followed by stomach cancer (22.9% vs.10.5%) and colorectal cancer (5.7% vs. 4.9%). Notably, among women, the incidence of cervical cancer (13.9%) and breast cancer (10%) has risen considerably, positioning these malignancies among the five most common cancers affecting Mongolian women *(1)*.

In men, lung cancer ranks as the third most common cancer, whereas among women lung cancer incidence (10.4% in males vs. 2.8% in females) does not appear within the top ten cancers. Pancreatic cancer, which had historically been common in both sexes, has shown a gradual decline over recent years, while colorectal cancer incidence continues to rise steadily. Overall, 61.9% of all cancers in Mongolia are considered preventable and associated with environmental or external risk factors, and approximately 71% are potentially detectable through early screening and diagnosis *(1)*.

Mongolia continues to rank among the highest in the world for liver cancer (96.1/100,000), stomach cancer (35.5/100,000), and esophageal cancer (15.7/100,000) (Table 1). Although Mongolia ranks 45th globally in cancer incidence, with 235.8 newly diagnosed cases per 100,000 population, it ranks first worldwide in cancer mortality, with 181.5 deaths per 100,000 population *(2)*.

In 2025, mortality is still particularly high for liver cancer (80.2/100,000), stomach cancer (31.5/100,000), and esophageal cancer (14.4/100,000). Approximately 65–70% of cancer cases continue to be diagnosed at advanced stages, although this proportion has gradually declined in recent years, reaching 59.7% in 2025, which is notable achievement.

The leading causes of cancer-related mortality are liver cancer (34.9%), stomach cancer (15.8%), lung and bronchial cancer (10%), esophageal cancer (6%), and pancreatic cancer (4.3%), which these five cancers together account for 74.1% of all cancer deaths (Table 2).

Liver and stomach cancers alone account for 51.7% of total cancer mortality. Mortality patterns are similar between men and women for these two cancers, with liver cancer accounting for 34.4% of male cancer deaths and 35.5% of female cancer deaths, while stomach cancer accounts for 19% and 8.3%, respectively *(1)*.

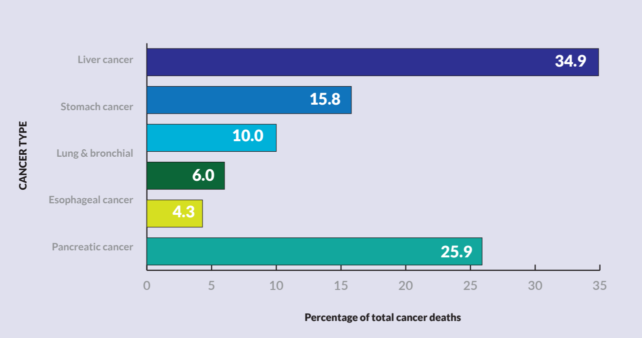
Unique pattern of cancer risk

According to the Global Burden of Disease study 2019, Mongolia had the world's highest age-standardized DALYs for liver cancer (2,558.1) in 2019. Alcohol-attributable DALYs (786.6) were 29 times higher than the global average (26.1), and liver cancer due to hepatitis C (752.6) and B (763.2) were 21.5 (35.0) and 10.9 (69.1) times higher, respectively. In 2019, liver cancer incidence due to alcohol consumption was 3.1 times higher for males than females, and hepatitis B was 2.7 times higher for males than females. However, the incidence of hepatitis C and NASH were slightly higher for females *(3)*. Deaths from liver cancer accounted for 9.51% (2,365) of total deaths in Mongolia in 2019, with a continuously increasing trend in the fraction of death compared to 1990, which was 11 times higher than the global average (0.86%), particularly in females with a 319.6% (95% UI 234.9–435.7) increase observed during the study period. Liver cancer due to hepatitis B, C, and alcohol each shared about one-third of liver cancer deaths.

Recent advances in cancer genomics, particularly the work of Josep M Llovet and colleagues, have revealed that hepatocellular carcinoma (HCC) in Mongolian patients exhibits distinct molecular characteristics associated with environmental exposures. These findings suggest that environmental carcinogens, including those found in polluted air, may play a previously underappreciated role in cancer development.

The study on Hepatocellular Carcinoma in *Mongolia Delineates Unique Molecular Traits and a Mutational Signature Associated with Environmental Agents* provides one of the most compelling pieces of evidence connecting environmental exposure to cancer in Mongolia. Key findings were 1) identification of unique mutational signatures in Mongolian HCC tumours; 2) evidence of DNA damage patterns consistent with environmental carcinogens which is coal combustion; 3) high tumour mutational burden compared to other populations due to combined risk factors; and 4) distinct genomic alterations not fully explained by viral hepatitis alone.

Table 2: **Leading causes of cancer mortality in Mongolia**



These results indicated that Mongolian patients are exposed to additional carcinogenic factors beyond infections, likely environmental in origin *(4)*.

At the same time, Ulaanbaatar experiences some of the highest levels of air pollution globally, particularly during winter time. This convergence of extreme environmental exposure and high cancer burden creates a compelling case for integrating environmental health into cancer control strategies. Given Mongolia's severe air pollution, it is biologically plausible that inhaled pollutants contribute to systemic carcinogenesis, including liver cancer. When we see in molecular level, the implications extend to other cancers, since airborne toxins enter circulation via the lungs, and triggers systemic inflammation which further promotes tumorigenesis throughout body, and similar mutational processes may occur in lung, bladder, and other tissues. Therefore, long lasting air pollution in Mongolia is considered a multi-organ carcinogenic exposure and would be counted one of biggest challenges in Mongolian public health. Therefore, Mongolians are exposed with a multi-hit model of carcinogenesis, where environmental pollutants amplify existing risks, unfortunately.

Air pollution and distinct mutational signatures in Mongolian HCC

Over the past three decades, Mongolia has experienced a steady increase in both the incidence and mortality of liver cancer. During the same period, rapid population growth, urbanization, extensive coal combustion for heating, and industrial expansion have substantially increased air pollution, particularly in urban areas. As a result, air pollution levels in Ulaanbaatar, the capital city of Mongolia, frequently rank among the highest in the world during the winter months. Despite growing concerns regarding its health impacts, insufficient air quality management and delayed mitigation measures have contributed to the continued deterioration of air quality across the country.

Rapid urbanization has transformed Ulaanbaatar into a densely populated metropolitan area where infrastructure development has struggled to keep pace with population

Figure 1: Air quality scene of Ulaanbaatar ger area *(iToim.mn.2019)*

growth. Approximately half of Mongolia's population resides in the capital city, with a large proportion living in ger districts that rely heavily on coal-based heating systems. During the winter season, emissions from household coal combustion, coal-fired power plants, and motor vehicles combine with temperature inversions that trap pollutants near the ground, resulting in extremely hazardous air quality (Figure 1).

Therefore, over the past three decades, Ulaanbaatar has become one of the most severely polluted cities in the world. During winter, concentrations of fine particulate matter (PM2.5) have frequently exceeded the World Health Organization (WHO) guideline levels by more than 20-fold, with daily average concentrations often reaching 550–650 μg m^3 during the coldest periods *(5)*.

Air pollution in Mongolia is characterized not only by its high concentration but also by its complex composition. Major pollutants include polycyclic aromatic hydrocarbons (PAHs), heavy metals such as arsenic and cadmium, volatile organic compounds (VOCs), and ultrafine particulate matter. Many of these substances are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC) (6). Consequently, the prolonged exposure of Ulaanbaatar residents to these pollutants may have contributed substantially to the country's current cancer burden and elevated cancer risk.

The human impact of cancer is evident throughout Mongolia, where the disease continues to impose a substantial burden on patients, families, and the healthcare system. Medical and public health professionals recognize that cancer is a multifactorial disease influenced by numerous genetic, behavioural, environmental, and social determinants. However, I was surprised when some officials questioned my public comments regarding the potential relationship between air pollution and cancer risk. While scientific debate is essential, dismissing the possibility of such a relationship overlooks a growing body of evidence linking long-term exposure to air pollution with increased cancer incidence and mortality.

One of the most compelling studies demonstrating the carcinogenic effects of air pollution was published in 2022. Study of "Hepatocellular Carcinoma in Mongolia Delineates Unique Molecular Traits and a Mutational Signature Associated with Environmental Agents" provided some of the strongest molecular evidence linking air pollution exposure to Mongolian liver cancer development.

This study identified four mutational signatures in Mongolian hepatocellular carcinoma (HCC), including a novel signature, SBS Mongolia, which was detected in 25% of cases and was strongly associated with exposure to dimethyl sulfate (DMS), a probable carcinogen linked to coal combustion *(4)*.

Nevertheless, skepticism regarding these findings persists despite the increasing strength of scientific evidence. Although all residents of Ulaanbaatar are affected by severe air pollution, the most vulnerable populations are those living in ger districts and young children. Residents of ger districts experience the highest levels of chronic exposure due to household coal combustion, poorer neighborhood air quality, and limited access to cleaner energy sources. These conditions contribute to a greater cumulative risk of developing pollution-related diseases, including various types of cancer.

Children are particularly vulnerable to air pollution, as exposure during critical stages of development can impair lung growth, compromise immune function, and adversely affect long-term health outcomes. Early-life exposure is of particular concern because of its potential to increase disease risk throughout the lifespan. Supporting this concern, Guo et al. (2019) reported that each 10 μg/m³ increase in long-term PM2.5 exposure was associated with a 22% increase in cancer mortality risk *(7)*. Given that PM2.5 concentrations in Ulaanbaatar have frequently exceeded this level by 20–30-fold over many years, the potential implications for future cancer burden and population health are substantial.

The findings from the study of "Hepatocellular Carcinoma in Mongolia Delineates Unique Molecular Traits and a Mutational Signature Associated with Environmental Agents" challenge the traditional view that liver cancer in Mongolia is driven primarily by viral hepatitis. Instead, it requires us to incorporating environmental risk into cancer control programmes, expanding prevention strategies beyond infection control and specifically, recognizing air pollution as a major carcinogenic exposure. Accordingly, reducing air pollution and strengthening population-based prevention strategies were identified as key priorities during the development of Mongolia's National Cancer Control Plan following the IAEA 2024 imPACT Review Mission.

Policy implications and future directions

So, it is well known that reducing air pollution should be one major opportunity for cancer prevention in Mongolia, as environmental exposures can be addressed through effective policies and infrastructure improvements. Key strategies could include reducing coal dependence through cleaner energy sources, improving housing and heating systems, expanding sustainable transportation, and strengthening urban planning. International partnerships can support these efforts through technical and financial assistance. Further research, including long-term exposure studies and integration of environmental data into cancer registries, is needed to strengthen the evidence base for policymaking. Beyond its health impacts, air pollution also creates substantial economic costs, making investments in clean air both a public health and economic priority.

The persistence of severe air pollution reflects longstanding challenges in environmental governance, policy implementation, and institutional continuity. Frequent administrative turnover and inconsistent prioritization of public health objectives have hindered the development of sustainable long-term solutions. Although the need to reduce air pollution and strengthen cancer prevention is widely recognized, implementation remains challenging without stable governance structures, institutional capacity, and sustained political commitment. So, it is unfortunate that Mongolian HCC has identified with as unique molecular traits with a high mutational burden that has affected by complex of factors and its novel mutational signature associated with genotoxic environmental factor, coal combustion, which had been present in this country for last three decades.

We have many bitter lessons. In the "Mongolia Sustainable Development Vision 2030," adopted by the State Great Khural in 2016, Mongolia committed to reducing cancer mortality from 128 deaths per 100,000 population to 105 during Phase I (2016–2020), 90 during Phase II (2021–2025), and 80 during Phase III (2026–2030) *(8)*. The reality, however, has moved in the opposite direction. Rather than falling to the targeted level of 90 deaths per 100,000 population by 2025, cancer mortality has risen dramatically to 176.2 deaths per 100,000 population *(1)*. This stark discrepancy reflects not merely a failure to achieve national health targets, but a broader failure of governance and health policy implementation.

Without meaningful reforms, the situation is likely to worsen. Persistent political interference in the health sector, unstable governance, limited institutional capacity, and the continued neglect of public health priorities have collectively undermined efforts to reduce the burden of cancer. Unless policymakers recognize public health as a national development priority and commit to evidence-based decision-making, the gap between policy aspirations and health outcomes will continue to widen.

At last, Mongolia represents a unique case where molecular oncology, environmental health, and public policy intersect. The genomic evidence from HCC studies provides that air pollution is not merely a background risk, it is a central driver of disease that must be addressed within non-communicable disease planning and cancer control frameworks. In otherwise, long-term exposure to severe air pollution will not only continue to deteriorate population health but may also contribute to cumulative genetic and epigenetic damage, increasing the burden of cancer and other chronic diseases in future generations. ■

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