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Oncologic burden in Ukraine: regional inequalities and environmental risk factors

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Abstract

This study investigated regional inequalities in cancer incidence in Ukraine and their potential links to environmental pollution. Using data from 26 Ukrainian administrative regions, we analyzed 50 cancer indicators – covering incidence, prevalence and mortality across population subgroups – and 25 environmental variables reflecting air, water and soil contamination, including emissions of methane, sulphur dioxide, ammonia, suspended particulate matter and radioactive waste. A total of 1,250 pair-wise Pearson correlations were computed, revealing 69 moderate-to-strong positive associations ($r \geq 0.3$), of which 23 were statistically significant at the 95% confidence level ($p < 0.05$). The most consistent associations were observed for methane emissions, which showed significant correlations with six cancers, including breast, uterine, skin and non-Hodgkin lymphomas. Sulphur dioxide, suspended particulates and non-methane volatile organic compounds also demonstrated significant associations, particularly with hormonally mediated cancers and urban cancer prevalence. Geographic disparities were further shaped by demographic structure, healthcare access and underreporting in conflict-affected regions. Spatial visualizations and heatmaps supported the identification of recurrent pollutant–cancer associations, suggesting systemic environmental contributions to cancer burden. These findings underscore the multi-factorial nature of cancer risk in Ukraine and highlight the need for integrated environmental monitoring, strengthened diagnostic infrastructure, and regionally tailored public health strategies to reduce environmentally mediated cancer incidence.

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Availability of data and material: the datasets on cancer incidence, prevalence, and mortality analysed during this study can be found in the National Cancer Registry of Ukraine (http://www.ncru.inf.ua). Environmental indicators analysed during this study can be found in annual statistical compendia «Environment of Ukraine», issued by the State Statistics Service of Ukraine (https://ukrstat.gov.ua/druk/publicat/Arhiv_u/07/Arch_dov_zb.htm)

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Introduction

Cancer is a leading cause of incidence and mortality worldwide, with growing attention focused on its environmental determinants. In Ukraine, it is a significant public health challenge, ranking second among causes of mortality and accounting for nearly 10% of all deaths (Kornus *et al*., 2023). While individual risk factors such as genetics and lifestyle remain critical (Goshayeshi *et al.*, 2019; 2025) an increasing body of evidence highlights the spatial variability of cancer incidence and its potential association with environmental exposures (Kiani *et al.*, 2021; Montazeri *et al.*, 2020). Understanding these spatial patterns would enable researchers to disentangle the contribution of environmental, socioeconomic, and healthcare-related determinants of cancer risk.

Ukraine presents a unique case for spatial epidemiological analysis of cancer. As a post-industrialized nation with significant environmental burdens – including legacy pollution, widespread agricultural chemical use and residual radioactive contamination – Ukraine exhibits marked regional disparities in oncologic outcomes (Shkolnikov *et al.*, 1999; Döbrossy, 2002). These characteristics make it an informative setting for studying the interaction

between environmental exposures and cancer incidence at a population level. Disparities are further compounded by recent armed conflict, which has disrupted healthcare systems, population distribution and environmental monitoring in affected areas. Despite this complex situation, comprehensive spatial studies integrating cancer epidemiology and environmental data remain limited.

This study addresses this gap by employing geospatial methods and integrating epidemiological and environmental data to characterise regional patterns of cancer incidence in Ukraine. By combining population-based cancer registry statistics with indicators of environmental pollution, the study seeks to provide a comprehensive overview of spatial disparities and to highlight regions where environmental exposure may contribute disproportionately to the cancer burden. The aim was to assess regional variations in cancer incidence and prevalence across 26 administrative regions of Ukraine and to examine their associations with selected environmental pollutants using geospatial and statistical methods, with the ultimate objective to identify priority regions for targeted public health interventions and to generate evidence to support improvements in diagnostic capacity and population health.

Literature review

Cancer remains one of the leading medical and social challenges globally, and researchers across the world devote significant attention to studying cancer incidence patterns and trends. Cancer incidence and mortality represent key indicators of public health across the world. According to the International Agency for Research on Cancer, regional and environmental factors contribute significantly to the cancer burden globally (Cancer topics, 2025).

Numerous studies emphasise that regional disparities in cancer incidence are often linked to environmental factors such as air and water pollution, industrial emissions, and the legacy of chemical-intensive agriculture (Fiore *et al*., 2025; Neupane *et al.*, 2024; Turner *et al*., 2020). In their study, Turmakhanbetov *et al.* (2024) analysed cancer incidence rates in Kazakhstan, highlighting regional disparities and challenges in oncologic care. The authors discussed the effectiveness of different treatment approaches and emphasised the need to expand screening programmes and adopt international treatment standards. This study provides valuable insights into the geographical aspects of cancer incidence and the improvement of healthcare organisations in Kazakhstan. Siegel *et al.* (2024) examined cancer incidence and mortality trends in the United States, presenting a comprehensive analysis of cancer burden and major epidemiological patterns. The study paid particular attention to regional variations in cancer incidence and highlighted the importance of adopting a geographic approach to cancer prevention and control. The authors underscored the need for regional prevention strategies and equitable access to healthcare services. The work by Sankaranarayanan *et al.* (2011) focused on survival disparities among cancer patients in 14 countries across Africa, Asia, the Caribbean, and Central America, depending on the level of healthcare system development. The study pointed to the urgent need for investment in public awareness, cancer registration, early detection programmes, healthcare infrastructure, and human resources to address these disparities effectively.

Forecasting future cancer burdens also receives substantial attention from international researchers. For example, Santucci *et al.* (2024) provided mortality projections for the European Union, the United Kingdom and five major European countries (France, Italy, Spain, Poland, and Germany). Using mortality data from the World Health Organization (WHO) and Eurostat, the statistical office of the European Union, the authors identified progress in cancer prevention and treatment and concerning trends. The study highlights persistent geographical inequalities, making it a valuable contribution to understanding the spatial dimensions of cancer burden in Europe. In Eastern Europe, particularly Ukraine, these influences are shaped by a complex interplay of historical industrial development, agricultural practices, environmental pollution, and healthcare inequalities (Shkolnikov *et al.*, 1999; Döbrossy, 2002). For Ukraine, these patterns are documented in the National Cancer Registry bulletins (NCRU) by year and the Ecological Passports of the regions of Ukraine, published by the Ministry of Environmental Protection and Natural Resources of Ukraine as well as the annual statistical compendiums Environment of Ukraine, issued by the State Statistics Service of Ukraine. Data show elevated cancer incidence in areas with high levels of pollutants – for instance, ammonia, sulphur dioxide, non-methane volatile organic compounds, particulate matter and radiation residues from historical contamination events. These correlations have been explored in national studies and suggest that environmental exposure contributes to regional cancer patterns.

Urban-rural differences further complicate the oncologic landscape of Ukraine. The National Cancer Registry consistently reports higher cancer incidence rates in urban populations compared to rural ones. This pattern is consistent with global trends (Bergin *et al.*, 2018; Hashibe *et al.*, 2018; Zahnd *et al.*, 2018), although rural areas may be underdiagnosed in Ukraine due to reduced access to screening and specialised medical care. Interestingly, ecological pressures often do not respect urban-rural divides: pollutants such as particulate matter, ammonia, and strontium-90 have been detected at harmful levels in both settings, suggesting shared environmental risks.

Many scientific studies in Ukraine have focused on the dynamics of cancer incidence. In particular, the work by Dumanskyi & Chekhun (2022) analysed cancer incidence trends in Ukraine for the years 1990, 2010 and 2020. The authors highlighted a significant increase in cancer prevalence, driven by worsening environmental conditions and population ageing, while mortality rates remained relatively stable. They pointed out challenges such as insufficient prevention, low public awareness, a lack of modern equipment in oncology centres, and ineffective palliative care and social support programmes. Several publications have addressed cancer incidence in a regional context. For example, Saveliev & Ziuzin (2024) studied one in Mykolaiv Region. Research by Kornus and co-authors (2022, 2024) focused on cancer incidence patterns in Sumy Region. The dynamics of malignant neoplasm incidence and mortality in Transcarpathian Region were examined by Zhero *et al.* (2024). Chernihiv region and its role in the cancer incidence structure of Ukraine were studied in the works of Slabkyi *et al.* (2024).

Materials and Methods

The analysis covers all 26 administrative regions (oblasts) of Ukraine, including urban and rural populations, for the most recent period before the first stage of the latest military conflict (2018–2022).

Data sources

Cancer incidence, prevalence, and mortality data were

obtained from the National Cancer Registry of Ukraine (NCRU), which provides annual statistics disaggregated by sex, age group, cancer type and region. Socio-demographic data, including urban-rural population distribution and population density, were sourced from the State Statistics Service of Ukraine. Environmental indicators were obtained from the Ecological Passports of the regions of Ukraine, published by the Ministry of Environmental Protection and Natural Resources of Ukraine; and annual statistical compendia 'Environment of Ukraine', issued by the State Statistics Service of Ukraine. All cancer indicators were standardised per 100,000 population (however, data from Donetsk, Luhansk, Kherson and certain other conflict-affected regions should be interpreted with caution, as healthcare infrastructure and reporting systems have been severely disrupted since 2014, leading to possible underestimation of the cancer incidence there).

Analytical approach

The study combined descriptive and inferential statistical methods. Descriptive statistics were used to characterise regional cancer indicators. Pearson correlation analysis was applied to assess relationships between cancer indicators and environmental variables. The statistical significance of Pearson correlation coefficients was evaluated using a two-tailed t-test with 24 degrees of freedom (based on the 26 regional observations). Correlations were considered significant at the 95% confidence level ($p<0.05$) if $r\geq0.404$. Correlations with $r\geq0.340$ were interpreted as marginally significant at the 90% confidence level ($p<0.10$). Because of data availability constraints, analyses were based on unadjusted regional rates. Potential confounders (age structure, socioeconomic status (SES), smoking, alcohol consumption, healthcare access) could not be explicitly controlled and could therefore bias correlation estimates.

Medical indicators

A total of 50 cancer indicators were analysed, including: i) overall cancer incidence and mortality for the total, urban, rural, male, female, working-age and paediatric populations; ii) incidence of specific cancer sites: trachea/bronchus/lung, stomach, prostate, breast, uterine body, cervical, ovarian, skin (melanoma and non-melanoma), lip, oral cavity, pharynx, oesophagus, colon, rectum, liver, pancreas, larynx, kidney, bladder, thyroid, brain, bone and joint cartilage; iii) incidence of haematological malignancies: Hodgkin lymphoma, non-Hodgkin lymphomas, multiple myeloma and leukaemias; iv) prevalence indicators: total and site-specific cancer patient cohorts under medical follow-up at year-end, including those for breast, uterine body, skin, childhood leukaemia and childhood lymphomas; and v) cancer mortality indicators: total, working-age and paediatric mortality due to malignant neoplasms.

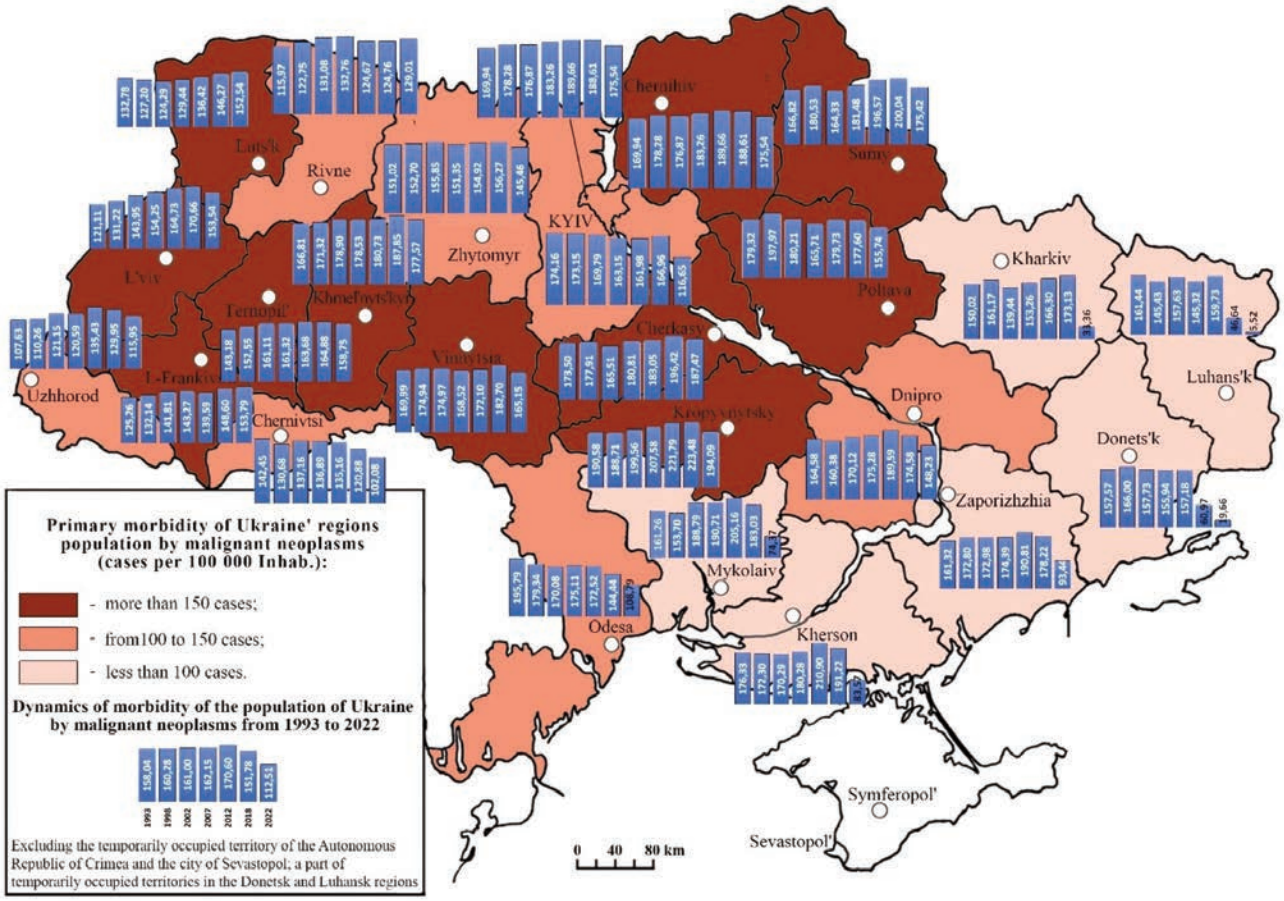

Figure 1. Regional distribution of primary incidence of cancer in Ukraine as of January 1st each year (cases per 100,000 population).

Environmental indicators

The 25 environmental indicators analysed included: i) air pollutant emissions from stationary sources: Sulphur Dioxide (SO_2), Nitrogen Dioxide, Carbon Monoxide, Non-methane volatile organic compounds (NMVOCs), ammonia, methane, carbon dioxide, suspended Particulate Matter (PM2.5), cyanides, fluorine and its compounds, chlorine and its compounds, bromine and its compounds, freons, persistent organic compounds with total emissions given as absolute, per unit area and per capita); ii) areas contaminated with radioactive contamination, such as ^{137}Cs, a man-made, radioactive Cesium isotope at levels below 185 kBq/m^2, ^{137}Cs at 185–555 kBq/m^2, ^{90}Sr, a man-made, radioactive strontium isotope, below 5.55 kBq/m^2, or at 5.55–111 kBq/m^2; iii) waste generation such as hazardous waste (classes I–III) and low-hazard waste (class IV) per capita; and 4) water pollution expressed as volume of polluted wastewater.

Data visualisation

Results of correlation analysis were visualised through choropleth maps, scatterplots and heatmaps to facilitate the interpretation of spatial and statistical patterns. Spatial patterns of cancer indicators and environmental variables were illustrated using choropleth maps produced in GIS software. Additional visualisations, including scatterplots and heatmaps of significant correlations, were generated using Python 3.11 (seaborn, matplotlib) in Google Colaboratory, which is a free, cloud-based Jupyter Notebook environment. Visualisation facilitated the identification of key pollutant drivers and supported the narrative in the Results and Discussion sections.

Results

Regional differences in primary cancer incidence in Ukraine

As of January 1st 2023, the primary cancer incidence rate in Ukraine was 233.8 cases per 100,000 population. Regional differences form a "geographical mirror" of environmental pressures, demographic structure and the ongoing impact of war (Figure 1). As can be seen from Figure 1, high incidence levels were recorded in 11 regions, with Cherkasy, Kirovohrad, Khmelnytskyi, Chernihiv and Sumy standing out. In Cherkasy, Kirovohrad and Khmelnytskyi – central regions with intensive agricultural production – extensive use of pesticides and agrochemicals combined

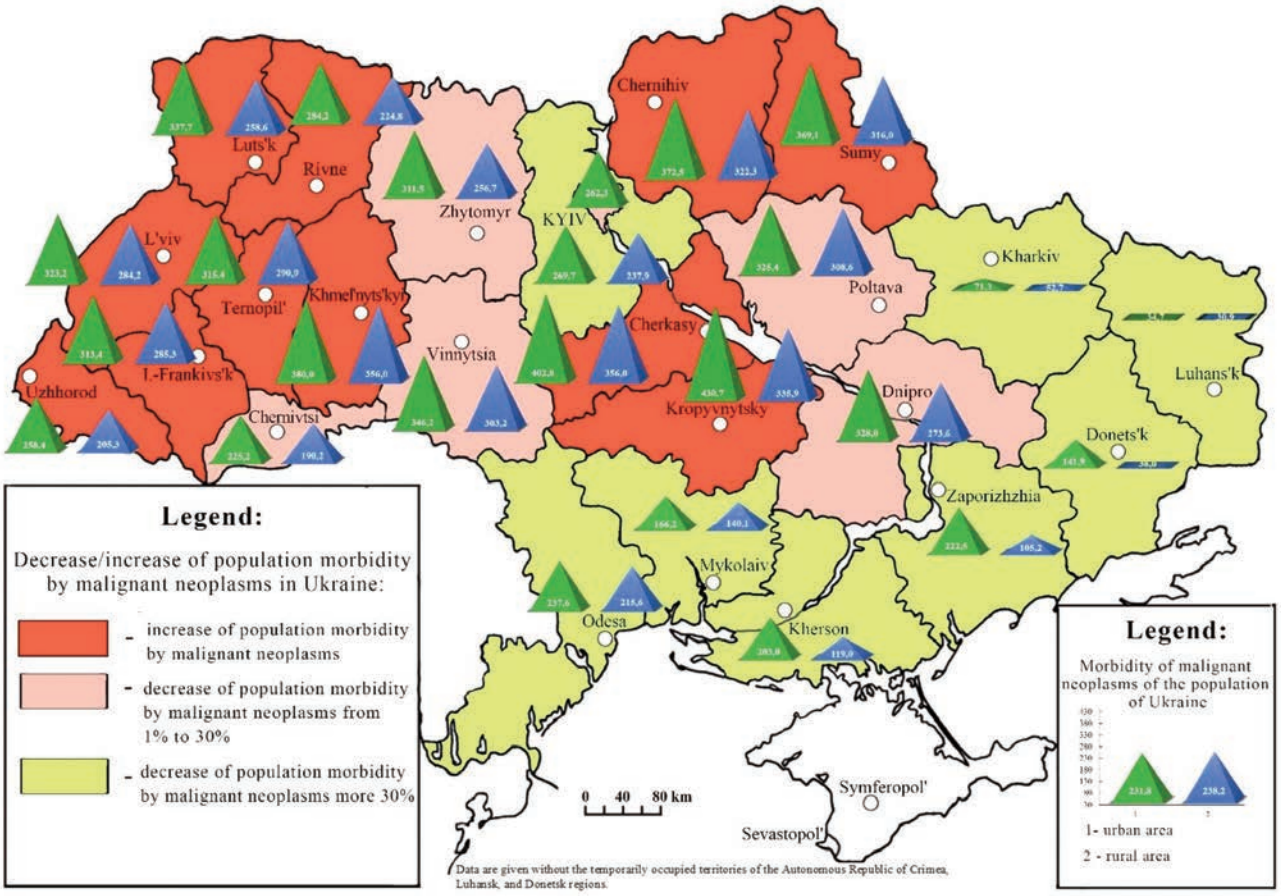

Figure 2. Incidence of malignant neoplasms among urban and rural residents of Ukraine as of January 1, 2023.

with emissions from local industries creates an environment conducive to malignant neoplasm development. Kirovohrad is further characterised by elevated background radiation from uranium deposits, which may significantly affect public health.

The Chernihiv and Sumy regions remain centres of oil and gas extraction, which contributes to contamination with carcinogens such as Polycyclic Aromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOCs), and PM2.5, all linked to increased risks of cancers of the respiratory system (Turner, 2020). Oil spills, drilling fluid leaks, and poor waste management contaminate soils and waters, enabling toxic compounds to enter the food chain and exert chronic carcinogenic effects. Heavy metals and chemical releases during extraction may damage DNA and trigger carcinogenesis, while workers in this sector face prolonged toxic exposure, further elevating their cancer risk.

In addition to 'technogenic' pressures, socio-demographic factors play a major role. Central Ukraine has a relatively high proportion of elderly residents, the age group most vulnerable to cancer. Other contributing risks include smoking, poor diet, sedentary behaviour and elevated stress, which collectively raise oncologic risk. Combined exposure to multiple toxic agents may have a cumulative effect, substantially increasing the probability of malignancy (EPA, 2025; Cancer Topics, 2025). Differences in healthcare infrastructure are part of the explanation for elevated rates. Regions with more developed medical systems and active screening programmes detect more cases at earlier stages, leading to a higher recorded incidence (but with better survival). Spatial cancer patterns therefore not only reflect biophysical and industrial pressures but also demographic profiles and healthcare accessibility. The interplay of agrochemical exposure, atmospheric pollution, socio-economic context, and robust diagnostic systems creates conditions for both higher risk and better detection. Elevated rates in these regions thus represent a multi-factorial phenomenon that demands interdisciplinary research and targeted public health responses. By contrast, in 2022 the lowest numbers of newly diagnosed cases were reported in Zaporizhzhia, Kherson, Mykolaiv, Kharkiv, Donetsk and Luhansk. This seemingly favourable picture likely reflects the war's impact – destruction of healthcare infrastructure, mass displacement and severe disruptions to medical services – making it difficult to assess the true epidemiological burden in these territories. Overall, these spatial patterns highlight the multi-factorial nature of cancer risk in Ukraine, where environmental exposures, demographic ageing, unequal healthcare access, and socioeconomic disparities collectively shape regional burdens. Understanding these interactions is essential for evidence-based policy and the development of targeted prevention strategies that

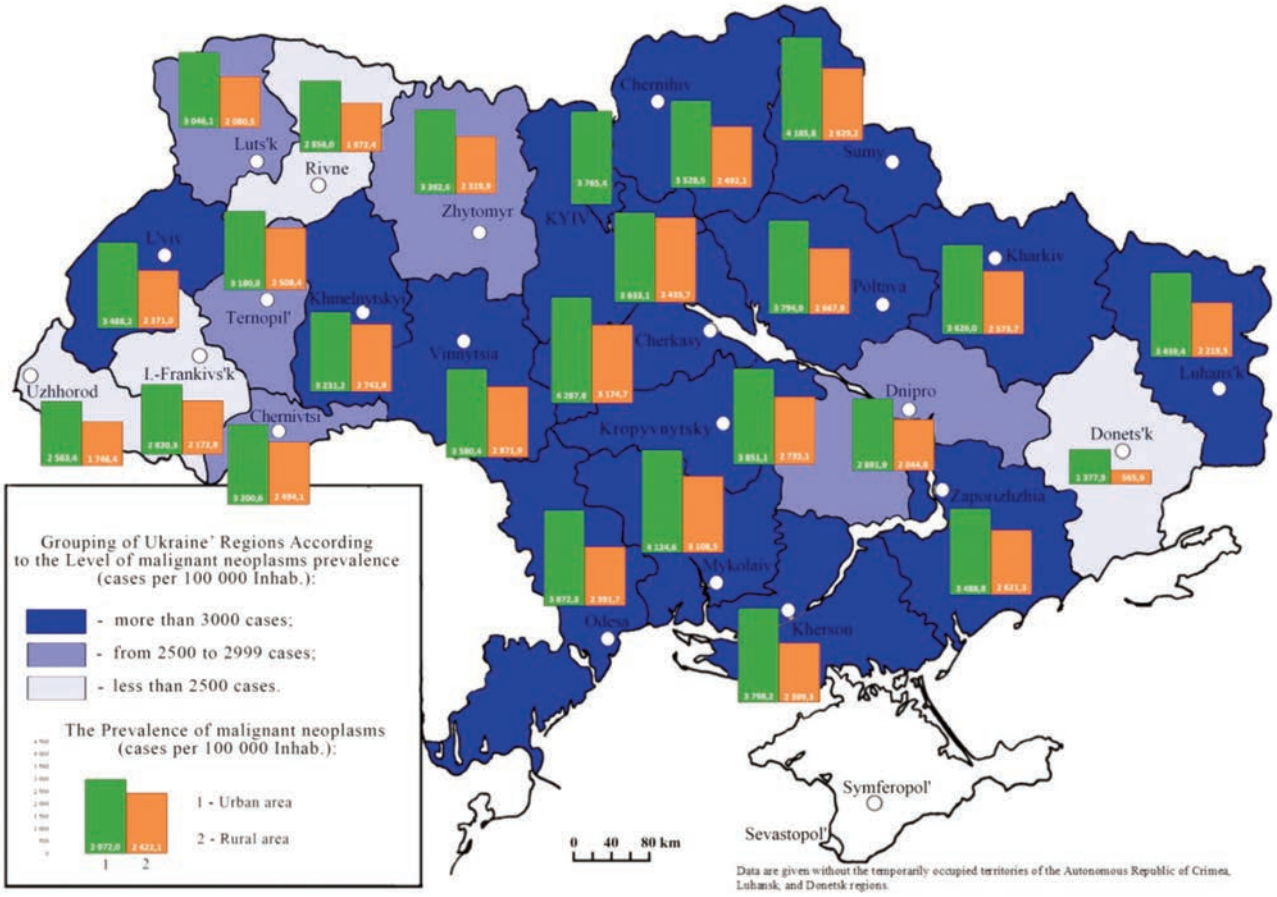

Figure 3. Prevalence of malignant neoplasms among the population of Ukraine as of January 1st, 2023.

address local needs. Examining urban–rural differences is particularly important, as it helps assess the combined impact of socioeconomic, environmental, and demographic factors on cancer incidence. Spatial differentiation of indicators allows for the identification of population-specific risk profiles and key contributing factors. As shown in Figure 2, the lowest primary cancer incidence rates among urban residents were observed in Mykolaiv (166.2 per 100,000), Donetsk (141.9), Kharkiv (71.3) and Luhansk (34.7). These figures should be interpreted with caution, as military conflict, population displacement, and limited healthcare access likely contribute to underreporting and incomplete surveillance. By contrast, the highest urban incidence rates were found in Kirovohrad (430.7), Cherkasy (402.8) and Khmelnytskyi (380 per 100,000). Among rural populations, Khmelnytskyi (356), Cherkasy (356), Kirovohrad (335.9), Chernihiv (322.3) and Sumy (316 per 100,000) showed the highest rates. Notably, Kirovohrad, Cherkasy and Khmelnytskyi consistently demonstrated elevated incidence across both urban and rural settings, pointing to broad regional effects of environmental and socio-economic risk factors. High rural incidence in Chernihiv and Sumy may also reflect ageing population structures and limited access to early cancer detection and treatment.

Regional inequalities in cancer prevalence in Ukraine

In 2022, the overall prevalence of malignant neoplasms among Ukraine's urban population was 2,972 cases per 100,000, though marked regional variation was observed. The lowest prevalence was recorded in Dnipropetrovsk (2,891.9), Rivne (2,856.0), Ivano-Frankivsk (2,820.3), Transcarpathian (2,563.4) and Donetsk (1,377.9) (Figure 3). By contrast, the highest prevalence occurred in Cherkasy (4,287.8), Sumy (4,185.8), and Mykolaiv (4,124.6), likely reflecting combined effects of environmental stressors, population ageing, healthcare access, and the quality of cancer diagnostics and registration.

Among rural populations, the national average prevalence was 2,422.1 per 100,000, with 14 regions exceeding this benchmark. As can be seen from Figure 3, the highest rates were observed in Kyiv (3,435.7), Cherkasy (3,174.7), Mykolaiv (3,108.5), Sumy (2,929.2) and Vinnytsia (2,871.9). The lowest were in Rivne (1,972.4), Transcarpathian (1,746.4) and Donetsk (565.9). Elevated prevalence in Kyiv, Cherkasy, Sumy, Vinnytsia and Mykolaiv may result from better access to diagnostics, more developed healthcare infrastructure, intensive agricultural activity, ageing populations and greater cancer awareness among primary care providers. Conversely, low prevalence in Rivne, Transcarpathian and Donetsk likely reflects limited medical access, under-diagnosis, labour migration (notably in Transcarpathian), and disrupted reporting systems due to conflict and territorial loss. Ethno-cultural factors and dietary traditions in some Western regions may also play a contributory role.

Urban–rural correlation in cancer prevalence

To explore the relationship between cancer incidence in urban and rural populations, Pearson correlation coefficients were calculated for three variables: urban prevalence, rural prevalence, and their difference, expressed as a new variable "Difference" (Figure 4). A very strong positive correlation was observed between urban and rural prevalence rates (r=0.98), indicating that regions with high urban rates generally also report high rural rates. Despite variations in absolute values, this close association suggests that similar regional risk factors – environmental, demographic, and healthcare-related – affect both population groups. In Cherkasy and Kirovohrad regions, for example, the urban prevalence were 4,287.8 and 4,124.6 per 100,000, while the corresponding rural figures were 3,174.7 and 3,108.5. Although the absolute differences exceed 1,000 cases, the proportional gap is moderate, reflecting shared exposure to regional determinants of cancer risk.

The correlation between urban prevalence and the urban–rural difference, on the other hand, was moderately strong (r=0.61), suggesting that larger gaps often occur where urban rates are highest. This may indicate additional urban-specific risks, including indus-

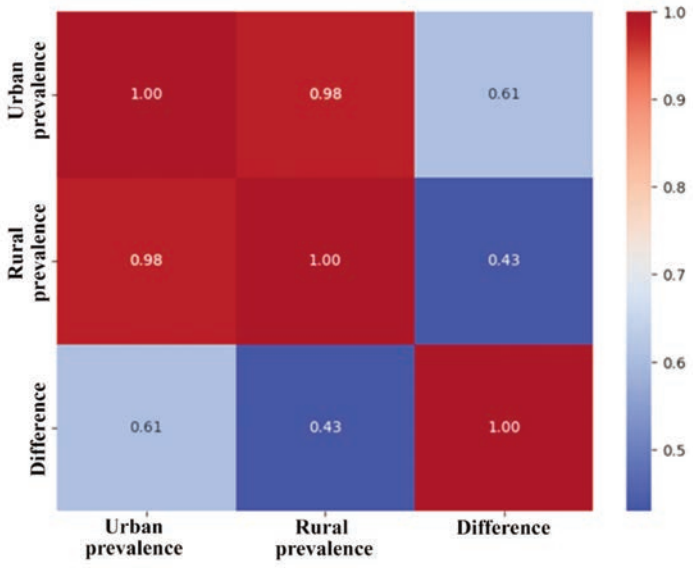

Figure 4. Correlation matrix of cancer prevalence indicators in urban and rural populations as of January 1st, 2023.

trial emissions, lifestyle factors, or greater diagnostic capacity. In Mykolaiv and Odesa regions, the urban prevalence values were 3,872.3 and 3,796.2 compared to the rural areas, where they were 2,391.7 and 2,399.3, producing differences of over 1,400 cases per 100,000. Such disparities point to a combination of environmental and socio-behavioural factors that may disproportionately affect urban populations. The correlation between rural prevalence and the urban–rural difference was weaker (r=0.43), suggesting that variations in rural cancer rates had only a minor influence on overall disparities. This likely reflects lower and less variable prevalence in rural areas, combined with barriers to healthcare access and under-diagnosis.

Across Ukraine, prevalence was consistently higher in urban than rural areas, with absolute values differing between regions but the overall pattern remaining clear. The sharpest contrasts were seen in Mykolaiv and Odesa, where urban prevalence exceeded rural rates by more than 1,400 cases per 100,000 population. Several factors may account for higher urban prevalence. Urban residents have better access to healthcare, including specialised diagnostics and oncologic centres, which increases detection and reporting. Industrial pollution of air, water, and soil in cities may also contribute through long-term exposure to carcinogens. In addition, urban lifestyles – characterised by higher stress, less physical activity, poorer diets, and greater tobacco and alcohol use – may further elevate risk. Lower prevalence in rural areas may not indicate genuinely lower incidence. Instead, it may stem from restricted access to diagnostic services and delayed detection. Demographic factors, such as a younger age profile in certain rural regions, may also partially explain the pattern. The strong correlation between urban and rural cancer prevalence (r=0.98) highlights the influence of shared regional risk factors across both settlement types. Yet notable absolute differences in some regions indicate additional urban-specific effects. High urban prevalence not only increases the overall disease burden but also widens the urban–rural gap, likely reflecting greater exposure to risk factors and more efficient diagnosis in cities. These results emphasise the need to interpret prevalence data within the context of regional and settlement characteristics, including healthcare accessibility, diagnostic capacity, and environmental conditions. They further underline the importance of cancer control strategies that account for urban-specific exposures while addressing persistent barriers in rural healthcare.

Demographic and gender-specific patterns in cancer prevalence

Demographic composition, particularly the proportion of older residents, remains a key determinant of cancer risk. Lifestyle-related factors such as smoking, poor diet, physical inactivity, and

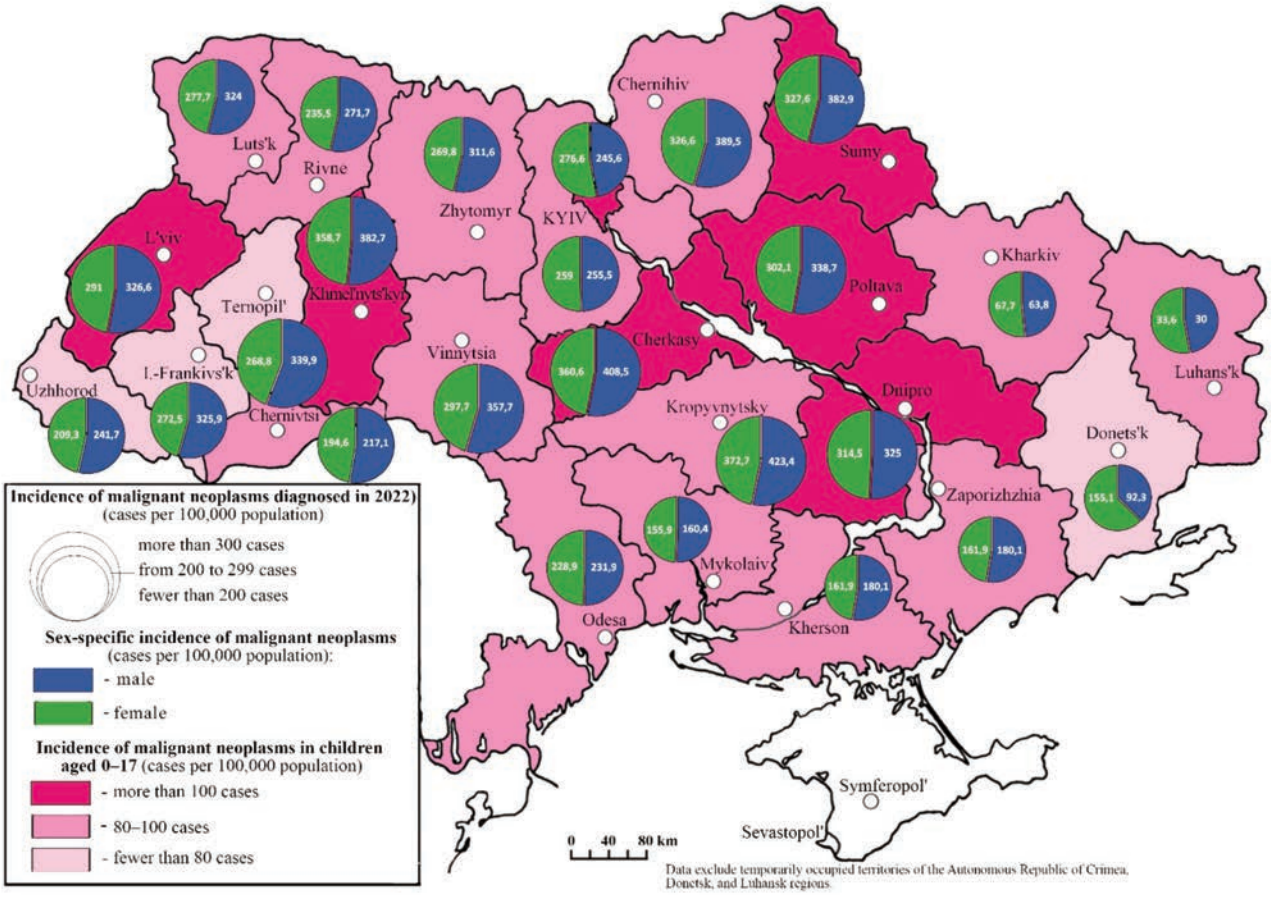

Figure 5. Gender differences in the incidence rate among the population of Ukraine as of January 1st, 2023.

chronic stress also contribute to higher incidence in some areas. In several regions, the combined influence of agricultural chemicals, industrial emissions, and socio-economic vulnerability creates a cumulative effect that may explain the elevated cancer burden. The demographic structure of the population, particularly the share of older individuals, strongly influences cancer risk. Regions with older age profiles generally report higher prevalence, while younger populations partly explain lower cancer burdens in some areas. Age is one of the most decisive risk factors, reflecting both the accumulation of genetic mutations and prolonged exposure to environmental and lifestyle carcinogens.

Gender differences in prevalence follow global patterns. Men show higher overall cancer rates, often linked to behavioural risks and occupational exposures, with lung and oesophageal cancers most common. In women, hormone-dependent cancers of the reproductive system are more frequent, influenced by endocrine, reproductive, and genetic factors. Childhood cancers present a distinct profile, dominated by leukaemia, lymphomas, and brain tumours. As of January 1st 2023, the incidence rate of childhood cancer in Ukraine was 89.1 per 100,000 population. As shown in Figure 5, the highest rates were recorded in Dnipropetrovsk (100.4), Sumy (104.7), Poltava (108.6), Lviv (113.5), Khmelnytskyi (114.6), Cherkasy (145.9) regions and Kyiv (104.5 per 100,000). These variations reflect not only environmental, medical, and social influences, but also differences in diagnostic organisation.

Correlations between environmental pollution and cancer incidence

To examine links between environmental quality and cancer incidence (see Materials and methods), 1,250 pair-wise Pearson correlation coefficients were calculated. Of these, 69 showed moderate to strong positive correlations ($r \geq 0.3$) and were therefore selected for further testing. Their significance was assessed with t-statistics and p-values, based on regional data from 26 Ukrainian regions.

Eleven correlations were significant at the 90% confidence level ($p<0.10$), indicating that a number of cancer outcomes are statistically associated with environmental indicators. These associations suggest potential links between cancer incidence and specific forms of air and water pollution (Figure 6). As illustrated in Figure 6, the strongest correlation was observed for bladder cancer, which was positively associated with NMVOC emissions ($r=0.395$). Childhood cancer mortality also showed a notable positive correlation with freon emissions ($r=0.384$). While these associations do not imply causality, they indicate possible links between environmental exposures and cancer outcomes. Moderately strong correlations were found between skin cancer and emissions of particulate matter ($r=0.378$), and between pancreatic cancer and particulate matter ($r=0.374$). Uterine cancer incidence demonstrated a positive association with NMVOC emissions ($r=0.369$). These results highlight recurring statistical links between cancer indicators and airborne pollutants. Additional significant associations included bone and joint cancers with per capita air pollutant emissions ($r=0.366$), and pharyngeal cancer with particulate matter ($r=0.351$). General cancer indicators also revealed noteworthy associations: overall cancer prevalence ($r=0.343$) and male cancer prevalence ($r=0.346$) were positively correlated with ammonia emissions, while male cancer prevalence was further associated with areas contaminated by ^{90}Sr ($r=0.351$).

Visualisation of the correlation matrix revealed the strongest associations at the 95% confidence level ($p<0.05$). Figure 7 displays a heatmap of 23 statistically significant positive correlations between cancer indicators and environmental variables across Ukraine's 26 administrative regions. This visual representation

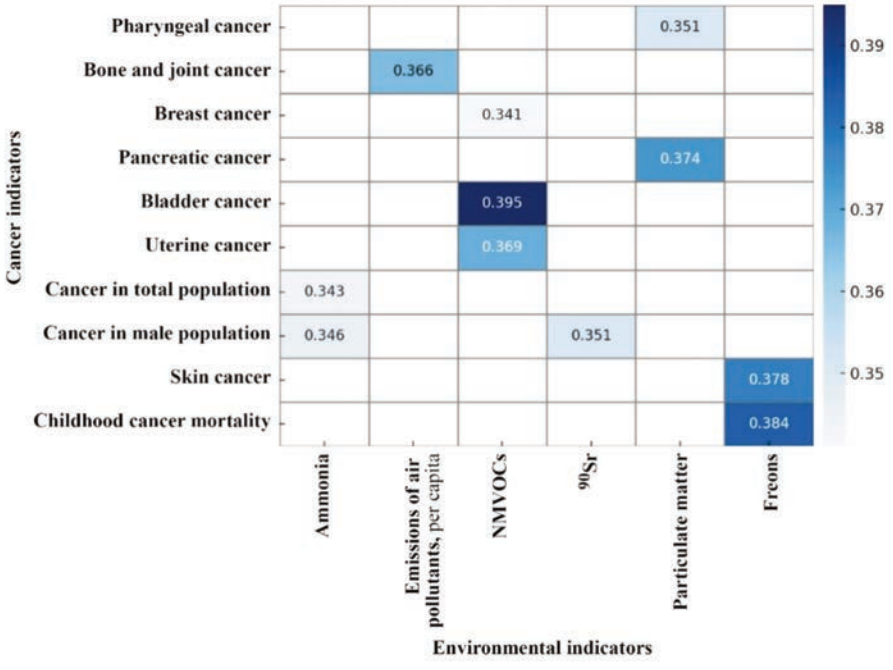

Figure 6. Heatmap of correlations between malignant neoplasm incidence and environmental indicators ($p<0.10$).

facilitates the identification of the most robust and recurrent relationships, highlighting several environmental factors consistently associated with cancer prevalence. As shown in Figure 7, the most frequently observed associations involved methane emissions, which demonstrated six statistically significant positive correlations ($p<0.05$). Methane was associated with the total number of registered cancer patients (r=0.582), cancer prevalence among urban populations (r=0.598), and the incidence of breast (r=0.527), skin (r=0.509), and uterine cancers (r=0.625), as well as non-Hodgkin lymphomas (r=0.427). The recurrence of these associations across multiple cancer types suggests that methane may act as an indicator of combined emissions from industrial and agricultural sources, reflecting a complex mixture of co-pollutants present in regions with high anthropogenic pressure. Sulphur dioxide also showed a notable pattern of statistically significant correlations, being linked to four cancer-related indicators: total cancer prevalence (r=0.466), urban cancer prevalence (r=0.413), breast cancer (r=0.479), and uterine cancer (r=0.428). These findings point to a consistent relationship between sulphur dioxide emissions and hormonally mediated malignancies, as well as overall cancer burden, particularly in industrially active regions.

Total emissions of air pollutants from stationary sources were significantly correlated with four cancer indicators, including breast cancer (r=0.457), skin cancer (r=0.423), brain cancer (r=0.420), and uterine cancer (r=0.446). These associations support the interpretation of total emissions as an integrative measure of regional pollution pressure. PM2.5 emissions were positively correlated with three indicators: total registered cancer cases (r=0.508), cancer prevalence among urban populations (r=0.534), and Hodgkin lymphoma incidence (r=0.430). These associations are consistent with the hypothesis that airborne particulates act as carriers of mutagenic and cytotoxic substances, thereby reflecting the general impact of air quality on cancer prevalence. Nitrogen dioxide emissions were significantly correlated with cancer prevalence in rural populations (r=0.431), a pattern that may be linked to local biomass burning, agrochemical application, or regional transport of atmospheric pollutants. NMVOCs demonstrated significant positive correlations with Hodgkin lymphoma (r=0.452)

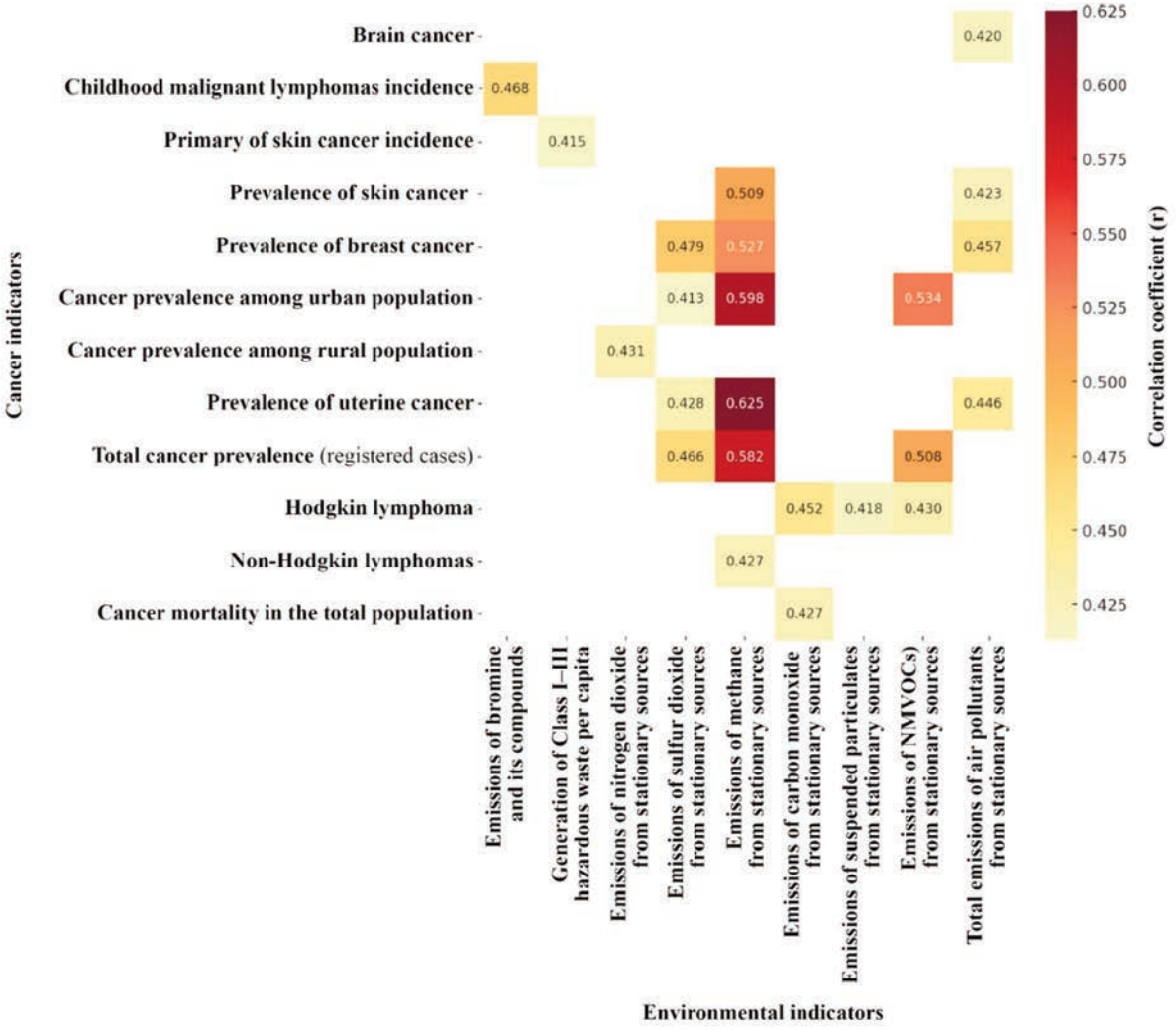

Figure 7. Heatmapofcorrelationsbetweencancerandenvironmentalindicators inUkraine ($r\geq0.4$, $p<0.05$).

and overall cancer mortality (r=0.427). These associations may reflect the contribution of NMVOCs and their photochemical transformation products to chronic exposure profiles in urban and industrial environments.

Additional statistically significant associations included emissions of bromine compounds with childhood malignant lymphoma incidence (r=0.468), generation of class I–III hazardous waste per capita with primary incidence of skin cancer (r=0.415), and carbon monoxide emissions with Hodgkin lymphoma incidence (r=0.418). Although less frequent, these associations are noteworthy and suggest the need for targeted toxicological and epidemiological follow-up in affected regions.

Discussion

The observed positive correlation between atmospheric ammonia emissions and overall cancer incidence, particularly among men, is consistent with previous research suggesting that ammonia may serve as an indicator of agricultural pollution rather than a direct carcinogen (Roney *et al.*, 2004; Wyer *et al.*, 2022). The correlation coefficients (r≈0.343–0.346) suggest a moderate association, which may reflect ammonia's potential role as a proxy for co-emitted pollutants from intensive livestock farming and fertiliser use. Ammonia emissions could therefore indicate a broader environmental burden that is linked to cancer outcomes across multiple regions. In addition to ammonia, male cancer incidence showed a statistically significant correlation with areas contaminated by ^{90}Sr at 5.55–111 kBq/m^2 (r=0.351). This finding aligns with evidence of long-term health effects of radionuclide contamination following the Chernobyl disaster (Repin *et al.*, 2000; Christodouleas *et al.*, 2011). As a beta-emitting isotope, ^{90}Sr is known to accumulate in bone tissue and has been associated with haematopoietic and musculoskeletal malignancies (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000; Glasco *et al.*, 2024). Although the present analysis cannot establish causation, the observed correlation is consistent with earlier studies highlighting possible delayed effects of ^{90}Sr exposure, particularly in populations with occupational or geographic proximity to contaminated areas.

Several cancer types demonstrated significant correlations with PM2.5 emissions, including pharyngeal cancer (r=0.351) and pancreatic cancer (r=0.374). These associations are in line with hypotheses that airborne particulates can act as carriers for carcinogens, potentially contributing to systemic effects (Peleman *et al.*, 2024; Bhavsar *et al.*, 2025). For pharyngeal cancer, the respiratory tract is the most direct route of exposure, whereas for pancreatic cancer, PM2.5 may reach distal organs via the bloodstream, transporting adsorbed carcinogenic substances such as PAHs and heavy metals (Loomis *et al.*, 2013). Such mechanisms suggest plausible biological pathways, though causality cannot be inferred from the ecological data alone. A distinct set of associations was identified between NMVOCs and cancers of the bladder (r=0.395), breast (r=0.341), and corpus uteri (r=0.369). Many NMVOCs, including benzene, toluene, and formaldehyde, are recognised carcinogens that may influence reproductive and urinary tract tissues (Shala *et al.*, 2023; Saeedi *et al.*, 2024). Their lipophilic properties facilitate accumulation in adipose tissue and potential systemic distribution, which could underlie observed associations. Prior studies have linked benzene, formaldehyde, and acrolein exposure to increased risks of breast and bladder cancers (International Agency for Research on Cancer, 2012; Xiong *et al.*, 2024), supporting the plausibility of these findings. The analysis also indicated significant correlations between freon emissions and both skin cancer incidence (r=0.378) and childhood mortality from malignant neoplasms (r=0.384). While freons are generally considered to have low direct toxicity, they are strongly implicated in ozone layer depletion (Freon, 2024). Increased ultraviolet radiation resulting from ozone thinning is a well-documented risk factor for skin cancers, especially in children, who are biologically more vulnerable to environmental exposures (Madronich *et al.*, 2015). Given the ecological design and the rarity of such findings, this association should be considered exploratory and interpreted with caution until confirmed by further toxicological or epidemiological studies. Among the environmental indicators showing associations at the p<0.10 level, ammonia emissions appeared most frequently, being correlated with overall cancer incidence, male cancer incidence, and the cancer patient population under medical follow-up. This recurrence may indicate that ammonia functions as a marker of cumulative exposure in regions with intensive agriculture or industry (Chen *et al.*, 2025). The recurrence of these associations raises the possibility that methane-related emissions serve as an indicator of broader environmental exposure patterns across multiple cancer types, potentially linked to co-emitted toxicants or combustion by-products. At the stricter 95% confidence level (p<0.05), further associations emerged, highlighting pollutants already noted at the 90% level but now in connection with other cancer types. This overlap suggests that pollutants such as methane, sulphur dioxide, and PM2.5 may exert multi-faceted influences across different cancer sites, or more likely, that they serve as indicators of complex pollutant mixtures. For instance, methane showed the strongest observed association, with a remarkably high correlation with uterine cancer prevalence (r=0.625), alongside significant links to breast cancer (r=0.527), skin cancer (r=0.509), and non-Hodgkin's lymphomas (r=0.427). While methane itself is not a direct carcinogen, its emissions often coincide with other volatile and combustion by-products, which may explain these consistent associations (Heddle, 1993; Kligerman *et al.*, 1995; Vyskocil, 1998; Thomas, 1981). SO_2 was also correlated with several cancer indicators, including breast and uterine malignancies (r=0.479 and r=0.428, respectively), urban cancer incidence (r=0.413), and the overall number of cancer patients (r=0.466). These associations align with evidence of SO_2 as a contributor to respiratory morbidity (Tomić-Spirić *et al.*, 2021; Cao *et al.*, 2022), though its carcinogenic potential is less clear. It may act indirectly by increasing susceptibility to other airborne toxicants through irritation and barrier impairment, thereby amplifying the impact of co-exposures such as PAHs and solvents. Our findings raise the possibility of a broader role of SO_2 in hormone-sensitive cancers, potentially via indirect pathways such as endocrine disruption.

Similarly, NMVOCs showed correlations with Hodgkin's lymphoma (r=0.452) and overall cancer mortality (r=0.427). Their diverse chemical composition and propensity for photochemical transformation into secondary pollutants (*e.g.*, formaldehyde, acetaldehyde) make them biologically plausible contributors to cancer risk (Kreja & Seidel, 2002a; Kreja& Seidel, 2002b; Seo, 2024). The consistency of NMVOC-related correlations across reproductive and hematologic malignancies supports their consideration as important environmental risk indicators, and the observed correlation with hematologic malignancies is consistent with prior toxicological evidence, though causality should be further investigated. PM2.5 remained significant across several out-

comes, including overall cancer incidence (r=0.508), urban cancer prevalence (r=0.534), and Hodgkin's lymphoma (r=0.430). These associations are consistent with prior studies identifying PM2.5 as a carrier for metals and carcinogenic hydrocarbons (Sui, 2022; Fang, 2023; Sakunkoo, 2022). The recurrent link between PM2.5 and cancer indicators highlights its potential as a key factor in environmentally mediated carcinogenesis, although this study cannot establish causality.

Taken together, the associations identified in this study underscore the multi-factorial nature of cancer epidemiology in Ukraine. Pollutants such as methane, sulphur dioxide, PM2.5, ammonia, and NMVOCs repeatedly emerged as significant correlates of cancer incidence and prevalence across multiple regions and cancer types. While these findings should not be interpreted as evidence of direct causality, they provide valuable ecological insights into environmental pressures that may shape cancer burdens. This warrants further investigation using individual-level data and refined exposure assessments to better understand causal mechanisms and to inform targeted prevention strategies.

The analysis of cancer indicators across Ukraine revealed pronounced geographical disparities. Urban populations consistently displayed higher prevalence compared to rural counterparts, a pattern shaped by both environmental exposure and healthcare access. While higher diagnostic capacity and availability of specialised medical centres may partly explain these urban–rural differences, the results also reflect the cumulative impact of industrial pollution, intensive agricultural practices, and lifestyle-related factors more common in cities. Conversely, lower prevalence in rural areas may not necessarily imply a lower true incidence but instead reflect barriers to early detection, under-diagnosis, and a relatively younger demographic profile.

Our correlation analysis, based on 1,250 pair-wise comparisons between cancer indicators and environmental variables, identified 69 statistically significant associations, of which 23 were confirmed at the 95% confidence level ($p<0.05$). These associations did not imply direct causality but nevertheless demonstrated consistent and biologically plausible links between environmental pollution and cancer burden. Methane, SO_2, PM2.5, NMVOCs, and radionuclide contamination (notably ^{90}Sr) were among the most recurrent environmental indicators associated with elevated cancer outcomes. While some of these associations were already evident at the 90% confidence level ($p<0.10$), their recurrence at stricter statistical thresholds reinforces their robustness and significance.

Methane emerged as the most prominent environmental variable, repeatedly associated with six distinct cancer outcomes, including uterine, breast, and skin cancers, as well as non-Hodgkin lymphomas. Although methane itself is not classified as a direct carcinogen, its recurring statistical association suggests that it may act as a proxy for broader industrial and agricultural emissions. Methane release often co-occurs with volatile organic compounds, combustion by-products, and secondary atmospheric pollutants formed through photochemical processes. The consistent appearance of methane across multiple cancer types points towards systemic exposure pathways and highlights the importance of using integrated pollution indicators as ecological markers in epidemiological research. Sulphur dioxide also demonstrated multiple associations, particularly with hormonally mediated malignancies such as breast and uterine cancers, as well as with urban cancer prevalence and overall cancer registry populations. While SO_2 is primarily recognised as a respiratory irritant, our findings suggest that it may act indirectly by enhancing the carcinogenic potential of co-emitted pollutants or by weakening protective mucosal barriers. These results underscore the compounding role of atmospheric pollutants in environmentally stressed regions.

PM2.5 emissions further reinforced concerns regarding the systemic toxicity of inhaled aerosols. Significant associations were observed with pharyngeal cancer, pancreatic cancer, Hodgkin lymphoma, and overall cancer prevalence. Given that fine particulates can act as carriers of polycyclic aromatic hydrocarbons, heavy metals, and other toxicants, their contribution to the observed cancer burden is both biologically credible and consistent with international evidence. NMVOCs, including compounds such as benzene, toluene, and formaldehyde, also showed significant associations with bladder, breast, and uterine cancers, as well as with overall cancer-related mortality, reflecting their well-established carcinogenic potential.

Radiological exposure continues to play a role in shaping cancer patterns in Ukraine. Our findings confirmed associations between areas contaminated with ^{90}Sr and male cancer incidence. This is consistent with the long-term consequences of the Chernobyl disaster and highlights the persistent carcinogenic risks of residual radionuclide contamination. The slow biological clearance of ^{90}Sr, coupled with its accumulation in bone tissue, raises particular concerns for haematological and skeletal malignancies, especially among occupationally exposed populations. Although some pollutants demonstrated fewer associations, their statistical significance warrants careful consideration. Bromine compounds, for example, showed an association with childhood lymphoma, which is consistent with evidence of the mutagenic and immunotoxic effects of brominated flame retardants and related compounds. Similarly, hazardous waste generation demonstrated a correlation with skin cancer prevalence, suggesting potential pathways through soil and water contamination or chronic dermal exposure. Taken together, these findings emphasise the multi-factorial and regionally mediated nature of environmental carcinogenesis in Ukraine. While the observed associations should not be interpreted as direct evidence of causality, their recurrence, statistical reliability, and biological plausibility highlight the importance of integrating environmental health considerations into cancer prevention and control strategies. Our results provide a quantitative, data-driven foundation for prioritising regulatory interventions, monitoring frameworks, and targeted public health policies. From a methodological perspective, this study demonstrates the value of combining geospatial visualisation with correlation-based approaches to detect patterns that may otherwise remain obscured in raw statistical data. Heatmaps and spatial clustering helped identify pollutants that repeatedly appeared across multiple cancer outcomes, thereby strengthening the case for their relevance in environmental oncology. This integrative approach is particularly valuable in settings where causal inference is limited by ecological data but where preliminary evidence can guide further research.

The policy implications of these findings are significant. Regions with higher cancer prevalence, particularly those characterised by intensive industrial or agricultural activity, require prioritised investment in environmental monitoring, cancer screening, and diagnostic infrastructure. Methane, SO_2, PM2.5, and NMVOCs may serve as priority indicators for environmental health surveillance. Strengthening cancer registries, improving the completeness of health reporting, and linking environmental and medical datasets will be essential steps towards reducing environmentally mediated cancer risks.

Methodological limitations

Our findings should be interpreted with caution, as the ecological design precludes causal inference and does not control for potential confounders. The nearly perfect correlation between urban and rural prevalence suggests that age structure, socioeconomic context, and healthcare access jointly influence cancer registration. Future research using spatial regression techniques (e.g., GWR, SAR models) and age-standardised, SES-adjusted rates is warranted to disentangle environmental from demographic and healthcare effects. With regard to conflict-affected regions, the apparently low cancer incidence reported in Donetsk, Krerson, Luhansk and certain other conflict-affected regions should not be interpreted as reflecting a genuinely reduced cancer burden. Rather, these figures are artefacts of severely disrupted healthcare infrastructure, population displacement, and incomplete reporting systems. This limitation is central to interpreting spatial patterns: the underestimation of incidence in conflict zones is likely substantial. Nevertheless, the broader regional associations identified in this study remain robust, as they are based on data from the majority of administrative regions where healthcare and reporting systems have been preserved.

Conclusions

Cancer remains one of the most pressing public health concerns in Ukraine, ranking second among the leading causes of death and contributing to nearly one-tenth of overall mortality. Despite official statistics indicating certain declines in incidence rates in recent years, these figures must be interpreted with caution, as they likely underestimate the true burden due to incomplete reporting from conflict-affected territories, disruption of healthcare systems, and population displacement. In this context, our study provides new and comprehensive evidence of regional inequalities in cancer outcomes and their associations with environmental factors. This study provides one of the most comprehensive assessments to date of the relationship between cancer burden and environmental factors in Ukraine. By documenting both regional disparities and pollutant–cancer associations, it highlights the urgent need for integrated environmental and public health interventions. While causality cannot be inferred, the consistent recurrence of certain environmental indicators suggests that they may serve as sentinel markers of risk. These findings should stimulate further epidemiological research, inform environmental regulation, and support the design of targeted cancer prevention strategies in environmentally burdened regions.

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