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Review article

Air Pollution, Microbial Exposure, and Lung Cancer Risk: Integrating One Health Concepts

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Abstract: Lung cancer remains one of the leading causes of cancer-related mortality worldwide, with increasing evidence highlighting the role of environmental and biological interactions in its development. This review explores the complex relationship between air pollution, the human microbiome, and lung cancer within a One Health framework. While smoking remains a major risk factor, air pollution has emerged as a significant modifiable environmental contributor, particularly in urbanized and industrial regions. Pollutants such as particulate matter (PM2.5 and PM10), nitrogen dioxide, and volatile organic compounds are associated with increased lung cancer incidence through mechanisms involving oxidative stress, chronic inflammation, and genetic damage. Recent research has also identified the lung microbiome as an important factor in respiratory health. Once considered sterile, the lungs are now known to host diverse microbial communities that play a role in immune regulation and inflammatory balance. Environmental exposure, particularly polluted air, can disrupt this microbial balance, leading to dysbiosis. Such microbial alterations may contribute to impaired immune responses and enhanced susceptibility to disease. This review further highlights the mechanistic links between air pollution-induced microbial dysbiosis and lung carcinogenesis. Key pathways include chronic inflammation, immune dysregulation, oxidative stress, epigenetic changes, and alterations in the tumor microenvironment. The interaction between the lung and gut microbiome (lung–gut axis) further emphasizes the systemic impact of environmental exposures. The One Health approach provides an integrated framework to understand these interconnected systems, emphasizing the relationship between environmental health, microbial ecosystems, and human disease. However, current research remains fragmented, with gaps in longitudinal data and integrated multi-omics studies.

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Introduction

Lung cancer remains one of the leading causes of cancer-related deaths worldwide, placing a significant burden on healthcare systems and communities. Despite advances in diagnosis and treatment, survival rates remain low, largely because the disease is often detected at a late stage. While tobacco smoking has long been recognized as the primary risk factor, a growing body of evidence highlights the important role of environmental exposures, particularly air pollution, in the development of lung cancer [1]. In many parts of the world, especially in rapidly urbanizing regions, individuals are continuously exposed to harmful pollutants such as fine particulate matter, industrial emissions, and vehicle exhaust, all of which contribute to increased cancer risk.

In response to mounting scientific evidence, the International Agency for Research on Cancer (IARC) officially classified outdoor air pollution and particulate matter as carcinogenic to humans [2]. This recognition marked a critical shift in how environmental health risks are understood, emphasizing that lung cancer is not solely a lifestyle related disease but also deeply influenced by external environmental factors. As a result, attention has increasingly turned toward understanding the broader biological mechanisms through which these exposures contribute to carcinogenesis [3].

One such emerging area of interest is the role of the human microbiome in cancer development. The microbiome, which consists of trillions of microorganisms residing in and on the human body, plays a crucial role in maintaining health, regulating immune responses, and influencing inflammation [4]. Recent research suggests that disruptions in microbial balance, often referred to as dysbiosis, may contribute to the initiation and progression of various cancers, including lung cancer. Environmental factors such as air pollution can alter the composition of the microbiome, potentially creating conditions that favor carcinogenesis [5]. This growing intersection between environmental exposures and biological systems has led to the increasing relevance of the One Health concept. One Health is an integrated approach that recognizes the interconnectedness of human health, animal health, and the environment. It emphasizes that health outcomes cannot be fully understood in isolation but must be examined within a broader ecological context. In the case of lung cancer, this perspective is particularly valuable, as it allows for a more comprehensive understanding of how environmental pollutants and microbial ecosystems interact to influence disease risk [6].

However, despite these advancements, the existing body of literature remains fragmented. Studies on air pollution, the microbiome, and lung cancer are often conducted independently, with limited integration of findings across these domains. This separation has made it challenging to fully understand the complex pathways linking environmental exposures to cancer development through microbial mechanisms. Therefore, the objective of this review is to bring together these distinct yet interconnected areas of research. By exploring the relationship between air pollution, microbiome alterations, and lung cancer within a One Health framework, this article aims to provide a more holistic understanding of the underlying mechanisms and highlight potential directions for future research and prevention strategies [7].

Methodology

This review was conducted using a narrative, semi-systematic approach to provide a comprehensive yet structured understanding of the relationship between air pollution, the microbiome, and lung cancer within a One Health framework. This design was selected to allow flexibility in exploring interdisciplinary evidence while still maintaining a transparent and reproducible process of literature selection and synthesis.

A thorough search of major scientific databases was carried out, including PubMed, Scopus, Web of Science, and Cochrane Library. These sources were chosen because they cover a wide range of peer reviewed studies across medical, environmental, and biological sciences. The search strategy combined key terms to capture relevant studies, using the expression: (“air pollution” AND “lung cancer” AND microbiome AND “One Health”). This approach helped identify research examining both direct and indirect links among environmental exposure, microbial alterations, and cancer development.

To ensure relevance and scientific quality, specific inclusion criteria were applied. Studies published within the last 10 to 15 years were prioritized to reflect current knowledge and recent advancements in the field. Both human studies and experimental research, including animal and laboratory-based investigations, were considered to provide a broader perspective on mechanisms and outcomes. Only peer-reviewed articles were included to maintain credibility and reliability.

Studies were excluded if they did not directly relate to the core themes of this review or lacked scientific rigor. Non-peer-reviewed sources, opinion pieces without supporting evidence, and articles focusing on unrelated diseases or exposures were omitted. This helped maintain a focused and high-quality evidence base.

The selection process followed the general principles of PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which support transparent reporting of literature screening and selection. Titles and abstracts were initially reviewed to remove irrelevant studies, followed by full-text assessments to confirm eligibility. Finally, the collected data were synthesized using a thematic integration approach. Instead of analyzing studies in isolation, findings were grouped into key themes such as environmental exposure pathways, microbiome alterations, and mechanisms of carcinogenesis. This allowed for a more connected interpretation of evidence and supported the development of a unified perspective aligned with the One Health concept.

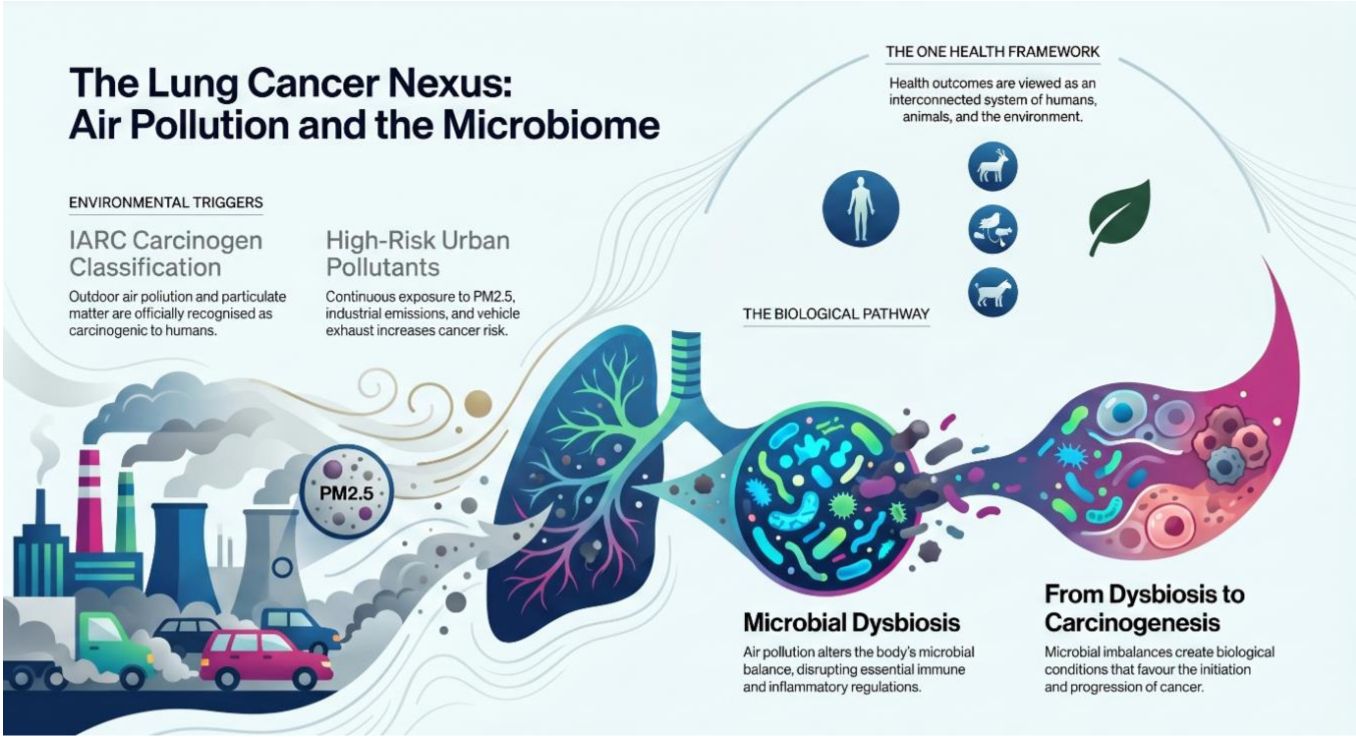

Figure 1. Environmental impact on lung microbiome diversity.

Air Pollution as a Risk Factor for Lung Cancer

Air pollution is now widely recognized as an important risk factor for lung cancer, especially among people who have never smoked. Continuous exposure to harmful pollutants in the air can damage lung tissue, trigger inflammation, and lead to long term changes that increase the risk of cancer. Both outdoor and indoor air pollution play a significant role, making this a global public health concern [8].

Types of Air Pollutants

Air pollution is made up of different harmful substances that vary in size and chemical nature. Among the most important are particulate matter, especially PM2.5 and PM10. These are tiny particles suspended in the air; PM2.5 is smaller and more dangerous because it can travel deep into the lungs and even enter the bloodstream. PM10 particles are slightly larger but can still affect the respiratory system [9].

Other common pollutants include nitrogen dioxide (NO_2), which mainly comes from vehicle emissions and industrial activities, and ozone, a gas formed when sunlight reacts with pollutants in the atmosphere. Volatile organic compounds (VOCs) are another group of harmful chemicals released from fuels, paints, and industrial processes. All these pollutants can irritate the lungs, cause oxidative stress, and damage cells, which may lead to cancer over time [10].

Epidemiological Evidence

A large number of studies have shown a strong link between air pollution and lung cancer. Research consistently finds that long term exposure to particulate matter, especially PM2.5, increases both the incidence of lung cancer and related deaths. People living in highly polluted areas are at a higher risk compared to those in cleaner environments [11].

Global health data also show that air pollution is one of the leading environmental causes of lung cancer. It contributes significantly to the overall disease burden, particularly in low and middle-income countries where pollution levels are often higher and regulations may be less strict. These findings highlight that air pollution is not just an environmental issue but also a major health risk [12].

Indoor vs Outdoor Pollution

Air pollution is not limited to outdoor environments; indoor air can also be highly polluted, especially in certain settings. Indoor pollution often comes from the use of biomass fuels such as wood, coal, or animal dung for cooking and heating. Cooking fumes, especially in poorly ventilated kitchens, can also release harmful particles and gases. In addition, exposure to secondhand smoke further increases the risk of lung damage and cancer [13].

Outdoor pollution mainly comes from traffic emissions, industrial activities, and urban development. However, the level of exposure can vary greatly depending on the region. For example, people living in urban or industrial areas are usually exposed to higher levels of pollution compared to those in rural areas. Similarly, individuals in low-income settings may face greater indoor exposure due to traditional cooking methods [14].

Microbial Exposure and Lung Microbiome

In recent years, the understanding of the human respiratory system has changed significantly. Earlier, it was believed that the lungs are completely sterile and free from any microorganisms. However, modern research has clearly shown that this is not true. The lungs actually contain a diverse community of microorganisms, including bacteria, viruses, and fungi, which together are known as the lung microbiome. This discovery has completely changed how scientists understand lung health and disease [15].

The lung microbiome is not present in large numbers like the gut microbiome, but it still plays a very important role in maintaining respiratory balance. These microorganisms interact closely with the immune system and help regulate how the body responds to external threats. In a healthy state, there is a balanced relationship between the host (human body) and these microbes. This balance helps in controlling inflammation, preventing infections, and maintaining normal lung function [16].

One of the most important functions of the lung microbiome is its role in immune regulation. It helps the immune system recognize harmful pathogens while avoiding unnecessary or excessive immune reactions. This is important because an overactive immune response can damage lung tissue, while a weak response can lead to infections. Therefore, a stable microbiome acts as a protective factor for respiratory health [17].

However, the composition of the lung microbiome is not fixed. It is highly influenced by environmental exposure. Every time a person breathes, they are exposed to a wide range of airborne particles, including dust, pollutants, and microorganisms. These environmental microbes can enter the respiratory tract and interact with the existing lung microbiome. Over time, this continuous exposure can shape and modify the microbial community inside the lungs [18].

Air quality plays a major role in this process. In polluted environments, the air contains harmful particles and fewer beneficial microorganisms. This can disturb the natural balance of the lung microbiome. On the other hand, in cleaner and more natural environments, there is greater microbial diversity, which may support a healthier microbial balance in the lungs [19].

Another important factor is lifestyle and living conditions. People living in urban areas are exposed to more industrial pollution and fewer natural microbes, while those in rural settings may encounter a more diverse range of environmental microorganisms through soil, plants, and animals. These differences in exposure can lead to variations in lung microbiome composition across populations [20].

Lung Microbiome Composition and Function

The lungs contain a variety of microorganisms, including bacteria, viruses, and fungi, although in smaller amounts compared to areas like the gut. This shows that the lung environment is not sterile, but rather a balanced ecosystem where microbes and the human body interact.

These microorganisms play an important role in regulating the immune system. They help the body recognize harmful pathogens and respond appropriately, preventing excessive inflammation. A stable lung microbiome supports normal immune function, while any imbalance may weaken the body’s defense and increase the risk of disease [18].

Environmental Microbial Exposure

The microbes present in the lungs are influenced by what we breathe in every day. Air contains tiny living particles known as bioaerosols, which include bacteria, fungal spores, and other microorganisms. These airborne microbes enter the respiratory system and can become part of the lung microbiome [21]. There is also a clear difference between urban and rural environments. Rural areas usually have higher microbial diversity due to natural surroundings like soil, plants, and animals. In contrast, urban areas often have lower diversity and may contain more pollution-related microbes. This difference in exposure can affect the composition of the lung microbiome and overall respiratory health [22].

Dysbiosis and Disease

When the normal balance of microorganisms in the lungs is disturbed, it is known as dysbiosis. This can lead to changes in microbial diversity and function, which may negatively affect health.

Research shows that dysbiosis is linked to several respiratory diseases, including chronic infections, asthma, and even lung cancer [23]. Reduced diversity or the presence of harmful microbes can trigger inflammation and damage lung tissue over time. These changes may create an environment that supports disease development and progression. Overall, maintaining a balanced lung microbiome is important for respiratory health, and disruptions in this balance can play a key role in disease [24].

Air Pollution–Induced Microbial Dysbiosis

Air pollution not only damages lung cells directly; it can also disturb the balance of microorganisms in the body. This disturbance, known as dysbiosis, affects both the lung and gut microbiome and can lead to long-term health problems. Increasing evidence shows that polluted air can change microbial composition and promote inflammation not just in the lungs, but throughout the body [25].

Mechanisms of Dysbiosis

Air pollutants can trigger several biological changes that lead to microbial imbalance. One major mechanism is oxidative stress, where harmful particles generate reactive oxygen species (ROS). These molecules can damage cells, proteins, and DNA, creating an environment that disrupts normal microbial communities [26].

Another important effect is the disruption of the epithelial barrier. The lining of the respiratory tract acts as a protective barrier, but exposure to pollutants can weaken it. When this barrier is damaged, harmful microbes and particles can enter more easily, disturbing the natural balance of the microbiome.

Chronic inflammation is also a key factor. Continuous exposure to polluted air keeps the immune system in an active state, leading to long-term inflammation. This ongoing inflammatory response can change the types and diversity of microorganisms present in the lungs and even affect the gut microbiome [27].

Lung Gut Axis

The lung and gut are closely connected through what is known as the lung–gut axis. This means that changes in one system can influence the other. The microbiome in both organs communicates through immune signals, metabolic products, and inflammatory pathways.

For example, disturbances in the gut microbiome can affect immune responses in the lungs, and vice versa. Air pollution that alters the lung microbiome may also lead to changes in gut bacteria, showing a bidirectional relationship between the two systems [28]. This connection plays an important role in regulating the body's immune system. A healthy balance of microbes supports proper immune function, while disruption in either the lungs or gut can lead to immune imbalance and increased disease risk [29].

Mechanistic Pathways Linking Pollution, Microbiome, and Lung Cancer

The relationship between air pollution, the microbiome, and lung cancer is highly complex and involves multiple overlapping biological processes. These factors do not act independently; instead, they continuously interact with each other at molecular, cellular, and systemic levels. Over time, these interactions can create a biological environment that supports the initiation and progression of cancer [30].

Air pollution is one of the main starting points in this process. When a person inhales polluted air, it introduces harmful substances such as fine particulate matter, toxic gases, and chemical compounds into the respiratory system. These substances not only irritate the lungs but also trigger bigger biological changes. One of the earliest responses is damage to lung cells and disruption of normal cellular function, which can gradually lead to long-term tissue injury [31].

At the same time, air pollution has a strong impact on the immune system. Continuous exposure keeps the immune system in a state of alert, leading to chronic inflammation. Instead of resolving quickly, this inflammation becomes persistent, which damages healthy cells and creates a stressful environment for tissue repair. Over time, chronic inflammation is known to increase the risk of abnormal cell growth, which is a key step in cancer development [32]. The microbiome adds another important layer to this process. Changes in microbial communities in the lungs and gut can significantly influence how the body responds to environmental stress. When air pollution disrupts the normal balance of microbes (dysbiosis), it can weaken protective immune responses and increase harmful microbial activity. These altered microbial patterns can further intensify inflammation and contribute to tissue damage [33].

In addition, microbial changes can influence how cells behave at a molecular level. Some microbial products, known as metabolites, can interact with human cells and affect processes such as cell growth, immune signaling, and DNA stability. In a disrupted microbiome, these signals may become harmful and support conditions that favor cancer development [34].

Another important mechanism involves oxidative stress. Air pollutants can generate reactive oxygen species (ROS), which are highly reactive molecules that damage DNA, proteins, and lipids. This damage can lead to genetic mutations, which are a key factor in cancer initiation [35]. When combined with chronic inflammation and microbial imbalance, the risk of cellular transformation increases even further.

There is also strong interaction between the microbiome and the tumor microenvironment. Once abnormal cells begin to develop, the surrounding environment plays a critical role in determining whether these cells grow or are eliminated by the immune system. A disrupted microbiome can weaken immune surveillance, making it harder for the body to detect and destroy early cancer cells. This allows abnormal cells to survive and multiply [36].

Inflammation and Immune Dysregulation

One of the main pathways linking air pollution to lung cancer is chronic inflammation. When harmful particles enter the lungs, they continuously irritate the tissue and activate the immune system. Instead of resolving quickly, this response can become long lasting [37]. Persistent inflammatory signaling can damage normal cells and disturb immune balance. Over time, the immune system may become less effective at detecting and removing abnormal cells. This condition, known as immune dysregulation, creates an environment where cancer cells can grow and survive more easily [38].

Genotoxic and Epigenetic Effects

Air pollution, especially fine particulate matter like PM2.5, contains harmful substances such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals. These components can directly damage DNA, leading to mutations that increase cancer risk [39].

In addition to direct genetic damage, these pollutants can cause epigenetic changes. This means they can alter how genes are expressed without changing the DNA sequence itself. Such changes may turn off protective genes or activate harmful ones, contributing to the process of carcinogenesis [40].

Microbiome Host Interactions

The microbiome also plays an active role in cancer development through its interaction with the host body. Microorganisms produce various metabolites that can influence inflammation, immune responses, and cell growth [41].

Some microbial products may promote protective effects, while others can support tumor development if the balance is disturbed. When air pollution causes dysbiosis, harmful microbial activities may increase, leading to conditions that favor carcinogenesis. This shows that the microbiome is not just a passive factor but an active participant in disease processes [42].

Tumor Microenvironment Modulation

The tumor microenvironment refers to the surroundings in which cancer cells grow, including immune cells, signaling molecules, and nearby tissues. The microbiome can influence this environment in several ways.

Changes in microbial composition can affect immune surveillance, which is the body’s ability to detect and destroy cancer cells [43]. If this process is weakened, cancer cells may escape detection and continue to grow. In addition, microbial signals can influence inflammation and tissue responses, further shaping the tumor environment.

Overall, these interconnected pathways highlight how air pollution and microbiome changes work together to increase the risk of lung cancer, making this a multi-layered and complex process [44].

One Health Perspective

The link between air pollution, the microbiome, and lung cancer cannot be fully understood by looking at human health alone. It requires a broader view that connects the environment, living organisms, and microbial systems. This is where the One Health approach becomes important, as it helps explain how different factors interact and influence disease risk [45].

Conceptual Framework

The One Health concept is based on the idea that human health, environmental conditions, and microbial ecosystems are closely connected. Instead of studying these areas separately, this framework brings them together to provide a more complete understanding of health and disease [46].

In the context of lung cancer, this means looking at how air pollution affects the environment, how it changes microbial communities, and how these changes impact human health. It highlights that disease development is not caused by a single factor, but by the interaction of multiple systems working together [47].

Environmental Drivers

Several large-scale environmental changes play a major role in shaping health outcomes. Urbanization, for example, leads to increased traffic, industrial activity, and population density, all of which contribute to higher levels of air pollution. Industrialization further adds to this burden through emissions from factories and energy production.

Climate change is another important driver. Rising temperatures, changes in weather patterns, and increased frequency of wildfires can worsen air quality and alter microbial environments [48]. These changes can influence both the type and distribution of microorganisms in the air, which may affect human exposure and health risks.

Together, these environmental drivers create conditions that increase exposure to pollutants and influence microbial balance, ultimately affecting the risk of diseases such as lung cancer [49].

Animal-Human Environment Interface

Humans, animals, and the environment share interconnected microbial ecosystems. Microorganisms move between soil, air, water, animals, and humans, creating a continuous exchange. This means that changes in one part of the system can affect the others [50].

For example, environmental microbes can enter the human body through air or contact, while animals can act as carriers of certain microorganisms. This interaction is especially important in understanding how microbial exposure shapes the human microbiome. In addition, zoonotic and environmental microbial exchange highlights how microbes can spread across species and environments. While not all of these microbes cause disease, changes in their balance can influence immune responses and overall health. This shared ecosystem perspective reinforces the importance of addressing environmental and microbial factors together when studying complex diseases like lung cancer [51].

Vulnerable Populations and Exposure Inequities

The health effects of air pollution and microbiome disruption are not evenly distributed. Some groups are more exposed to harmful environments or more sensitive to their effects, which increases their risk of developing diseases like lung cancer. Understanding these differences is important for identifying high-risk populations and planning effective prevention strategies [52].

Urban populations are among the most affected groups due to higher exposure to traffic emissions, industrial pollutants, and dense living conditions. People living in large cities are often exposed to polluted air for long periods, which increases the risk of lung damage and microbial imbalance. Limited green spaces and poor air quality in crowded areas can further worsen health outcomes.

Occupational exposure is another major factor. Individuals working in industries such as construction, mining, manufacturing, and transportation are often exposed to dust, chemicals, and fumes on a daily basis. This repeated exposure can lead to chronic inflammation, respiratory problems, and long-term changes in the microbiome, all of which increase cancer risk [53].

People living in low- and middle-income countries face additional challenges. These regions often have higher levels of both indoor and outdoor pollution due to rapid urbanization, weak environmental regulations, and reliance on biomass fuels for cooking and heating. Limited access to healthcare and awareness also contributes to delayed diagnosis and poorer outcomes [54]. Genetic susceptibility also plays a role in determining how individuals respond to environmental exposures. Some people may be more vulnerable due to inherited differences in how their bodies process toxins, repair DNA damage, or regulate immune responses. This means that even at similar levels of exposure, the risk of developing lung cancer can vary from person to person [55].

Prevention and Control Strategies

Reducing the risk of lung cancer linked to air pollution and microbial imbalance requires a combination of environmental, clinical, and policy-based strategies. Since the problem is multi factorial, effective prevention must also work at different levels, from reducing pollution exposure to improving early detection and exploring new biological approaches [56].

Environmental Interventions

One of the most important steps in prevention is improving air quality. This can be achieved through strict air quality regulations that set safe limits for pollutants and ensure regular monitoring of environmental conditions. Governments and regulatory bodies play a key role in enforcing these standards.

Emission reduction is another critical strategy. This includes controlling industrial emissions, promoting cleaner energy sources, and encouraging the use of public transport or electric vehicles. Reducing the release of harmful gases and particulate matter directly lowers exposure and helps protect public health over time [57].

Clinical and Public Health Approaches

From a healthcare perspective, early detection is essential in reducing lung cancer mortality. Screening programs for high-risk individuals can help identify the disease at an earlier and more treatable stage. This is especially important for people living in highly polluted areas or with long term exposure.

Risk stratification is also useful in public health planning. It involves identifying individuals or groups who are at higher risk based on factors such as exposure level, occupation, smoking history, and genetic background. This allows for more targeted prevention and monitoring strategies [58].

Microbiome Based Interventions

An emerging area of research focuses on modifying the microbiome to improve health outcomes. Although still in early stages, approaches such as probiotics and microbiome modulation are being explored for their potential to restore microbial balance and reduce inflammation [59].

These interventions aim to support a healthy microbial environment in the body, which may help strengthen immune function and reduce disease risk. However, more research is needed before these strategies can be widely applied in clinical practice [60].

One Health Policy Integration

Effective prevention also requires coordination across different sectors, which is the core idea of the One Health approach. Environmental agencies, healthcare systems, and policy makers need to work together to address shared risks.

Cross sector collaboration can help develop integrated policies that target pollution control, public health protection, and environmental sustainability at the same time. By combining efforts across human health, environmental protection, and microbial research, more comprehensive and effective prevention strategies can be developed [61].

Challenges and Limitations

Although research on air pollution, microbiome changes, and lung cancer is increasing rapidly, there are still several important limitations that make it difficult to draw clear and definite conclusions. These challenges are related to study design, data availability, measurement methods, and the complexity of biological systems involved.

One of the main challenges is the heterogeneity of exposure measurement. Different studies assess air pollution in different ways, such as using fixed air monitoring stations, satellite-based models, or short-term personal exposure measurements. Each method has its own strengths and weaknesses, but because they are not standardized, the results often vary from one study to another. This makes it difficult to directly compare findings or establish a clear dose–response relationship between pollution exposure and lung cancer risk [62].

Another major limitation is the lack of longitudinal microbiome studies. Most of the current research on the lung and gut microbiome is cross-sectional, meaning it captures data at only one point in time. This does not show how microbial communities change over months or years after continuous exposure to air pollution. Since cancer development is a slow process, long-term studies are essential to understand how gradual microbial changes contribute to disease progression. Unfortunately, such studies are still limited in number and scope [63].

In addition, there is a lack of integrated datasets that combine environmental exposure data, microbiome profiles, immune responses, and clinical outcomes in a single unified system. Most studies focus on only one aspect, such as either pollution exposure or microbial composition, rather than connecting all relevant factors. This fragmented approach limits the ability to understand the full biological pathway from exposure to disease [64].

Another important issue is variability in microbiome analysis techniques. Different laboratories use different sequencing technologies, sample collection methods, and data processing pipelines. This lack of standardization can lead to inconsistent results, making it harder to reproduce findings across different populations and studies.

Finally, there is also a geographical and population bias in existing research. A large portion of studies comes from high-income countries, while low- and middle-income regions where pollution levels are often higher are underrepresented. This creates gaps in understanding how these relationships behave in more heavily exposed populations [65].

Future Directions and Research Gaps

Future research in the field of air pollution, microbiome changes, and lung cancer is moving toward more integrated and advanced approaches. Although current studies have provided valuable insights, there are still many gaps that need to be addressed to fully understand disease mechanisms and improve prevention strategies.

One important future direction is multi-omics integration. This approach combines different layers of biological data, such as genomics, microbiome profiling, and exposome analysis. The exposome includes all environmental exposures a person experiences throughout life. By combining these datasets, researchers can better understand how genetic factors, microbial changes, and environmental exposures interact to influence lung cancer development [66].

Another key need is the development of large-scale longitudinal cohort studies. These studies follow individuals over long periods of time, allowing researchers to observe how continuous exposure to air pollution affects the microbiome and cancer risk. Unlike cross-sectional studies, longitudinal designs can help identify patterns of disease progression and provide stronger evidence for cause-and-effect relationships [67]. The use of AI-based exposure modeling is also an emerging and promising area. Artificial intelligence and machine learning can help estimate individual exposure levels more accurately by combining data from air quality sensors, satellite imaging, and personal activity patterns. This can improve risk prediction and help identify high-risk populations more effectively than traditional methods [68].

In addition, there is growing interest in precision prevention strategies. This approach focuses on tailoring prevention methods based on an individual's genetic profile, environmental exposure, and microbiome composition. Instead of applying general recommendations to everyone, precision prevention aims to provide personalized interventions that are more effective in reducing lung cancer risk [69].

Conclusion

Air pollution is now clearly recognized as one of the major and modifiable risk factors for lung cancer. Continuous exposure to harmful environmental pollutants such as particulate matter, gases, and toxic chemicals contributes significantly to lung damage and increases the long-term risk of cancer development. This makes air quality a key target for prevention strategies worldwide. The One Health framework provides a more complete and holistic way of understanding these connections. By integrating human health, environmental conditions, and microbial ecosystems, it helps explain how different systems interact to influence disease risk. This approach emphasizes that health issues like lung cancer cannot be addressed in isolation but require a broader ecological perspective. Overall, there is a strong need for more integrated research that combines environmental science, microbiology, and clinical data. At the same time, coordinated policy action is essential to reduce pollution, protect vulnerable populations, and support early prevention strategies. A combined effort from researchers, healthcare systems, and policymakers is necessary to effectively address this growing global health challenge.

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