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REVIEW ARTICLE

The Impact of Air Pollution on Cardiopulmonary Health: Molecular Mechanisms, Preventive Strategies and Role of Physiotherapy

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ABSTRACT

Air pollution poses a critical threat to global health, particularly impacting the cardiopulmonary system through oxidative stress, systemic inflammation, and immune dysregulation. Key pollutants such as particulate matter (PM), nitrogen oxides (NOx), sulphur dioxide (SO2), and volatile organic compounds (VOCs) exacerbate conditions like asthma, chronic obstructive pulmonary disease (COPD), and cardiovascular diseases. This review examines the molecular mechanisms underlying these effects, highlighting the role of reactive oxygen species (ROS), inflammatory mediators, and epigenetic modifications. Additionally, we explore mitigation strategies, including environmental policies, technological advancements in air quality improvement, and personal protective measures. A significant focus is placed on the role of physiotherapy in managing air pollution-related respiratory complications, emphasizing pulmonary rehabilitation techniques, breathing exercises, and airway clearance strategies. Understanding these mechanisms and interventions is crucial for developing comprehensive public health policies and clinical guidelines aimed at reducing morbidity and mortality associated with air pollution exposure. By integrating molecular research with preventive and therapeutic approaches, we can enhance patient outcomes and reduce the burden of air pollution-related diseases.

KEYWORDS

• Air Pollution • Global health • Air quality index • Chronic obstructive pulmonary disease (COPD) • Cardiovascular Disorders • Role of physiotherapy

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INTRODUCTION

Air pollution is a major public health crisis, contributing to an estimated 6.7 million deaths worldwide in 2019 and nearly 7 million fatalities each year. Harmful pollutants like particulate matter, ozone, and nitrogen dioxide are the main culprits behind these alarming figures.[1] In India, outdoor air pollution alone led to over 1.7 million deaths in 2016, with illnesses such as stroke, heart disease, and lung cancer being the most common consequences.[2] Currently, India's Air Quality Index (AQI) stands at 146, which is classified as poor, while Delhi faces even worse conditions with a hazardous AQI of 197. Both outdoor and indoor pollution have severe health impacts, significantly increasing the risk of respiratory and cardiovascular diseases.[3]

Polluted air is a growing nature concern that strongly affect human well-being, particularly by increasing the risk of heart and lung diseases. The rapid expansion of industries, urbanization, and a heavy dependence on motor vehicles have contributed to the rising levels of harmful pollutants in the air. Some of the most common pollutants include particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3).[4] Long-term exposure to these pollutants can have severe health consequences, affecting both the respiratory and cardiovascular systems. Conditions such as Bronchial asthma, chronic obstructive pulmonary disease (COPD), lung carcinoma, and various cardiovascular disorders (CVDs) are closely linked to bad air property. Pollution of air continues to rise, it not only affects individuals but also places a burden on healthcare systems worldwide. Addressing this issue requires urgent action through stricter regulations, sustainable urban planning, and the promotion of cleaner energy sources to reduce harmful emissions and protect public health.[5]

The detrimental effects on the lungs and heart arise from the inhalation of toxic particles and gases, triggering a series of molecular responses that involve inflammation, oxidative stress, and activation of the immune system.[6] Individuals with preexisting respiratory or cardiovascular conditions are particularly at risk, often experiencing worsened symptoms and increased mortality rates.[7]

A comprehensive understanding of the molecular mechanisms by which air pollution impacts cardiopulmonary health is essential for formulating effective preventive measures to reduce these health risks.[8]

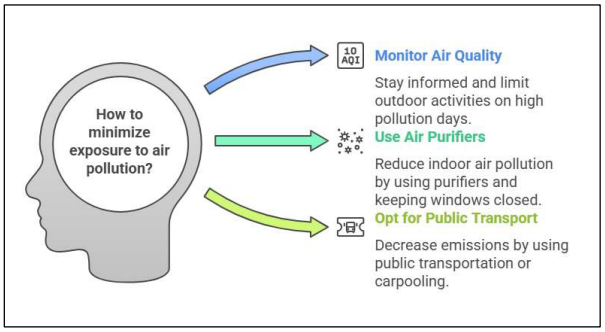

Fig. 1: How to minimize exposure to air pollution

Understanding how pollution contributes to disease progression is crucial for developing effective interventions the adverse consequences of air pollution on cardiopulmonary health are primarily driven by mechanisms of inflammation and oxidative stress, which are integral to the development of conditions such as atherosclerosis, myocardial infarction, and pulmonary fibrosis.[9] Fine particulate matter, especially PM2.5, is a significant factor in these biochemical disturbances.[10]

These minuscule particles can infiltrate the lungs, leading to chronic inflammation and disrupting normal pulmonary function. Furthermore, prolonged exposure to air pollution can induce systemic repercussions, including endothelial dysfunction, which compromises vascular health and elevates blood pressure, thereby heightening the risk of cardiovascular diseases.[11,12] In light of the extensive effects of air pollution, it is essential to implement preventive measures at both individual and governmental levels to mitigate exposure.[13]

Such measures may encompass enhancing air quality through more stringent regulations, fostering the development of green spaces, advocating for cleaner technologies, and promoting lifestyle modifications that reduce exposure during periods of elevated pollution.[14] The adoption of these strategies has the potential to significantly alleviate the global burden of cardiopulmonary diseases.[15]

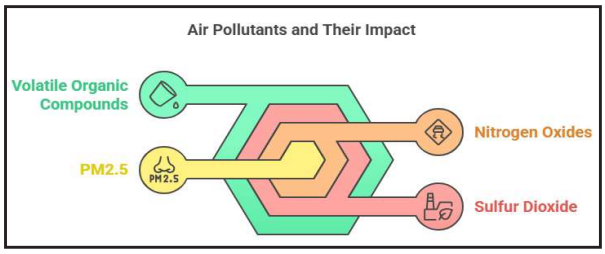

Fig. 2: Air pollutants and their impact

MAJOR AIR POLLUTANTS AND THEIR SOURCES

1. PM2.5 Particles

Tiny PM2.5 molecules are compact to enter the bronchus and even the bloodstream, posing serious health risks. Long-term exposure can increase the likelihood of respiratory diseases, heart complications, and even lung cancer.[16]

2. Nitrogen Oxides (NOx)

These pollutants primarily come from burning fuels in vehicles, power plants, and industrial facilities. A key component, nitrogen dioxide (NO_2), can irritate the airways, worsening asthma and reducing lung function. Prolonged exposure may also make people more vulnerable to respiratory infections.[17]

3. Sulfur Dioxide (SO_2)

Burning coal and oil in power plants and industries releases sulfur dioxide into the air. This gas can trigger breathing difficulties, especially for individuals with asthma, leading to symptoms like wheezing and shortness of breath. It also contributes to fine particulate matter and acid rain, both of which further harm respiratory health.[18]

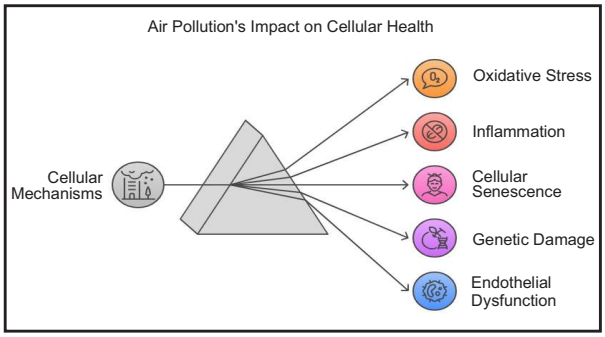

Fig. 3: Air pollution's impact on cellular health

4. Volatile Organic Compounds (VOCs)

Emitted from industrial activities, vehicle exhaust, and household products like paints and cleaners, VOCs can lead to serious health concerns. They contribute to ground-level ozone and secondary organic aerosols, which can cause oxidative stress and inflammation in the lungs. Some VOCs, like benzene, are known carcinogens and may also harm the liver, kidneys, and nervous system.[19]

MOLECULAR MECHANISMS OF IMPACT

1. Oxidative Stress

Breathing in PM2.5 particles can trigger the production of harmful molecules called reactive oxygen species (ROS). When these molecules overwhelm the body's natural defense system, they can damage proteins, lipids, and even DNA in lung tissues. This oxidative stress plays a key role in conditions like chronic obstructive pulmonary disease (COPD) by increasing inflammation, weakening the immune system, contributing to emphysema, and impairing the lungs' ability to clear mucus.[20]

2. Inflammation

PM2.5 exposure activates inflammatory responses in the body, particularly through the Transcription factor kappa B (NF-κB) pathway. This result in to the release of inflammation provocing chemicals like IL-6 and TNF-α, which can cause chronic airway inflammation and scarring (fibrosis) a major feature of COPD. Studies have shown that PM2.5 exposures in the lungs increases oxidative stress and worsens conditions like emphysema by amplifying inflammatory reactions.[21]

3. Endothelial Dysfunction

Pollutants in the air can interfere with the body's ability to produce nitric oxide, a molecule essential for healthy blood vessels. This disruption can lead to blood vessel constriction and increase the risk of atherosclerosis, a major contributor to heart disease. Inflammation and oxidative stress further damage the blood vessels, and recent research suggests that autophagy (the body's cell-cleaning process) may also play a role in this process.[22]

4. Epigenetic Changes

Air pollution can affect how genes function without altering their actual structure. Environmental toxins, including PM2.5, may trigger changes in DNA methylation and histone modifications, which can influence immune responses and tissue repair. These

epigenetic shifts might explain how air pollution contributes to various health issues, including increased risks of blood clotting and inflammation-related diseases.[23]

Cardiopulmonary Diseases Associated with Air Pollution

1. Asthma Exacerbations & COPD Progression

Exposure to pollutants like Inhalable particles and reactive organic gases (ROGs) can trigger and worsen asthma attacks. These harmful substances increase airway sensitivity, leading to excessive mucus production and making breathing more difficult. Pollutants also cause oxidative stress and inflammation in the respiratory system, resulting in airway constriction and a heightened reaction to allergens.Long-term exposure to air pollution plays a crucial role in the development and worsening of Chronic Obstructive Pulmonary Disease (COPD). Constant exposure to pollutants leads to ongoing airway inflammation and structural damage. Over time, this can harm the protective epithelial cells lining the lungs, reduce the efficiency of mucus clearance, and promote fibrosis (scar tissue formation). These changes contribute to the restricted airflow that defines COPD, making it increasingly difficult for affected individuals to breathe properly.[25]

2. Ischemic Heart Disease (IHD):

Fine particulate matter (PM2.5) can enter the bloodstream, triggering widespread inflammation and oxidative stress. These harmful effects engage in vital role in the formation with instability on atherosclerotic plaques—fatty deposits that build up inside arteries. When these plaques become unstable, they increase the chances for heart function impairment and other serious cardiovascular events.[26]

Exposure to air pollution has been closely linked to higher blood pressure, which can contribute to hypertension and heart disease. This occurs due to several factors, including damage to blood vessel linings (endothelial dysfunction), imbalances in the nervous system that regulate heart function, and chronic inflammation. Over time, these changes put extra strain on the heart, increasing the likelihood of cardiovascular complications such as strokes and heart attacks.[27]

3. Carcinogenic Effects of PAHs:

Polycyclic aromatic hydrocarbons (PAHs) are harmful chemicals released into the air during the burning of fossil fuels and other combustion processes. These substances are known to be highly carcinogenic, meaning they can cause cancer. When inhaled, PAHs can interact with the DNA of bronchial epithelial cells, leading to genetic mutations that may trigger the development of lung cancer. Long-term exposure to these pollutants significantly increases the risk of lung cancer, highlighting the serious health consequences of air pollution.[28]

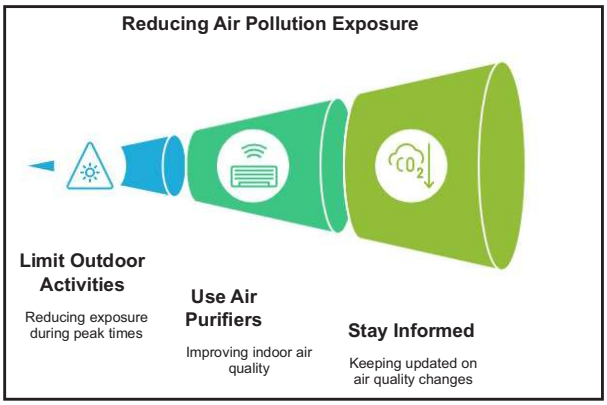

Fig. 4: Reducing air pollution exposure

4. Preventive Strategies

1. *Policy-Level Interventions:* Enhanced Emission Standards: The implementation of rigorous standards for industrial and vehicular emissions has demonstrated effectiveness in mitigating air pollution. A notable example is the Clean Air Act in the United States, which has led to a marked reduction in the concentration of key pollutants, thereby contributing to improved public health outcomes.[29] Clean Energy transition: Shifting towards geothermal energy sources significantly curtails the emissions of sulfur dioxide (SO_2) and volatile organic compounds (VOCs). Policies that advocate for clean electricity standards and zero-emission vehicle regulations play a crucial role in facilitating this transition.[30]
2. *Technological Solutions:* HEPA Filter Air Purifiers: Upper level-Proficiency Particulate Air (UPPA) cleaners are highly helpful in eliminating Respirable particles within indoor air, thus decreasing exposure to harmful pollutants. The

innovation of portable air purifiers further enhances individual protection against air pollution.[31] Personal Air Quality Monitors: Real-time air quality monitoring devices empower users to make informed choices regarding their surroundings, enabling them to avoid areas with high pollution levels and minimize exposure. These devices are increasingly available and serve as essential tools for managing personal health.[32]

3. *Lifestyle Modifications:* Protective Strategies: The use of masks in areas with elevated pollution levels can significantly reduce the inhalation of harmful particles. Furthermore, quitting smoking removes an Utmost origin of indoor polluted air and lowers risk of respiratory illnesses [33]. Antioxidant-Rich Diet: Incorporating foods high in antioxidants, such as vitamins C and E, may help alleviate oxidative stress caused by air pollutants, potentially providing protective health benefits.[3s4]
4. *Community Education:* Awareness Campaigns: Informing communities about the advantages of active transportation methods, including walking and cycling, can contribute to a decrease in vehicle emissions. These efforts not only enhance air quality but also encourage physical well-being.[35]

Implementing these strategies collectively can bring about significant Enhancement in air Property and people's well-being. Ongoing research and policy development are important to notice the evolving problems posed by air pollution.

ROLE OF PHYSIOTHERAPY

Bad quality air represents a condemning threat to nature which has been associated with numerous detrimental effects on human health, particularly concerning the cardiopulmonary system. The underlying molecular pathways through which air pollution intensifies cardiopulmonary disorders encompass oxidative stress, inflammation, and cellular injury, all of which can contribute to chronic respiratory functioning affection as well as cardiovascular conditions (including hypertension, atherosclerosis, and heart failure). The role of physiotherapy is vital in enhancing the prognosis for individuals suffering from these ailments, facilitating functional recovery, and mitigating further harm.[36]

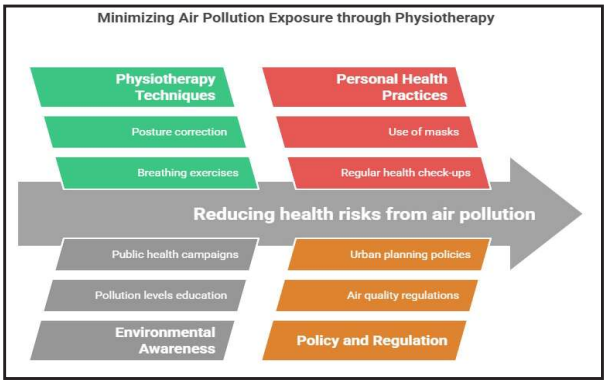

Fig. 5: Minimize air pollution exposure through physiotherapy

Physiotherapy is essential in the management of conditions such as asthma, COPD, and other respiratory disorders, all of which can be worsened by air pollution. The methodologies employed by physiotherapists include: Additional physiotherapy interventions include inspiratory muscle training (IMT) to strengthen respiratory muscles, positional therapy to optimize lung function, and the use of oscillatory positive expiratory pressure (OPEP) devices to clear airways. Clinical trials have demonstrated that these techniques improve lung capacity, reduce dyspnea, and enhance quality of life in individuals affected by pollution-induced respiratory diseases.

1. Breathing Exercises: Physiotherapists instruct patients in various controlled breathing techniques, including pursed-lip breathing and diaphragmatic breathing, which aid in decreasing the effort required for breathing and enhancing lung function.[37]

2. Pulmonary Rehabilitation: For those with chronic respiratory issues aggravated by air pollution, pulmonary rehabilitation programs have demonstrated effectiveness in improving lung capacity, boosting exercise tolerance, and alleviating dyspnea (shortness of breath). These programs also emphasize patient education to empower individuals in managing their conditions and alleviating pollution-related symptoms.[38]

3. Airway Clearance Techniques: Physiotherapists implement a range of methods, such as postural drainage, chest

percussion, and vibration therapy, to assist in the removal of mucus from the airways, which is particularly beneficial for patients with obstructive airway diseases.[39]

4. Exercise Training: Consistent physical activity guided by a physiotherapist can enhance endurance and alleviate cardiovascular stress in individuals with respiratory ailments exacerbated by air pollution. Activities such as aerobic workouts and resistance training contribute to the fortification of respiratory muscles and the enhancement of cardiovascular well-being.[40]

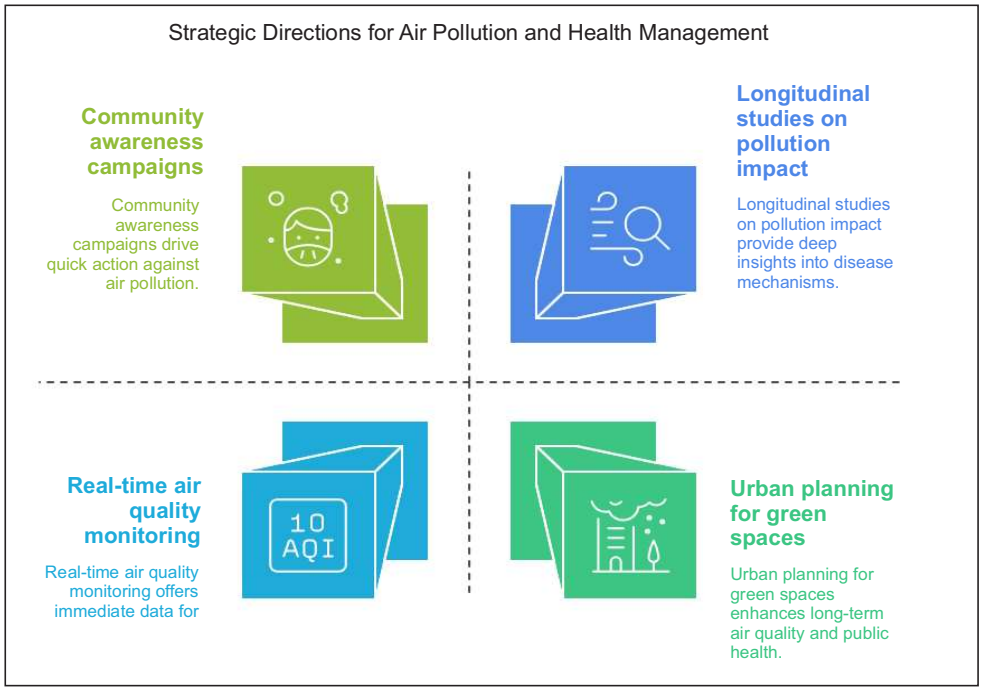

Fig. 6: Strategic Directions for air pollution and health management

FUTURE DIRECTIONS

1. Advanced Research on Molecular Mechanisms: Conduct longitudinal studies to better understand the interplay between specific air pollutants (e.g., particulate matter, ozone) and molecular pathways such as oxidative stress, inflammation, and epigenetic modifications leading to cardiopulmonary diseases.

2. Personalized Preventive Strategies: Develop tailored interventions based on genetic and epigenetic predispositions to air pollution susceptibility. Leveraging omics technologies (genomics, proteomics) can help create customized protective measures for high-risk populations.

3. Improvement in Air Quality Monitoring: Implement real-time and localized air pollution monitoring systems to provide granular data that can guide public health advisories and policies effectively. Such systems should integrate machine learning models for predicting high-risk exposure periods.

4. Policy Interventions and Urban Planning: Advocate for stricter air quality regulations targeting industrial emissions, vehicular pollution, and deforestation. Urban planning initiatives should prioritize green spaces and adopt pollution-absorbing infrastructure to mitigate pollutant levels.

5. Community and Global Awareness Campaigns: Promote awareness campaigns emphasizing the health impacts of air pollution and preventive practices such as wearing masks, using air purifiers, and supporting clean energy initiatives. Collaborative global efforts are crucial for addressing transboundary pollution.

CONCLUSION

Air pollution is a pervasive yet often overlooked driver of global morbidity and mortality, exerting significant impacts on the cardiopulmonary system. Understanding

the molecular mechanisms underlying these effects and developing comprehensive preventive strategies are critical to reducing its health burden. Achieving this vision requires coordinated action among policymakers, healthcare providers, and communities to foster a future of cleaner air and improved public health.

Conflicting Interest: None

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