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RESEARCH ARTICLE
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THE NEXUS OF CLIMATE CHANGE, AIR QUALITY AND HUMAN HEALTH IN CITIES: IMPACTS, SOLUTIONS AND STRATEGIES.

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ABSTRACT

This article reviews recent literature on the health impacts of climate change and air pollution, highlighting the benefits of policy actions that reduce greenhouse gas and air pollutant emissions. By synthesizing existing research, the article aims to inform decision-making and policy development that addresses the complex relationships between climate change, air quality, and human health, ultimately promoting more effective strategies for mitigating these global health challenges .Climate change poses a profound threat to human health, with far-reaching consequences that are both direct and indirect. Rising global temperatures are linked to increased morbidity and mortality due to extreme weather events, heat stress and altered patterns of disease transmission. Air pollution, particularly in urban areas with high levels of anthropogenic activity, exacerbates these health impacts, with pollutants like ozone, particulate matter, nitrogen dioxide, and sulfur dioxide contributing to respiratory and cardiovascular diseases. The interrelationship between climate change and air quality is complex, with climate change influencing the formation and dispersion of air pollutants. Mitigating these impacts requires a multifaceted approach, including reducing greenhouse gas emissions, transitioning to cleaner energy sources and implementing policies to improve air quality. Adaptation strategies, such as developing climate-resilient infrastructure and promoting public health interventions, are also crucial. This review highlights the impact, need for both short-term and long-term strategies to address the health impacts of climate change and air pollution, emphasizing the importance of considering the most vulnerable populations and fostering international cooperation to address this global health challenge

INTRODUCTION

Climate change is a pressing global issue that affects not only the environment but also human health in profound ways. Rising temperatures, extreme weather events, and altered ecosystems contribute to a wide range of health problems, from heat stress and respiratory diseases to vector-borne illnesses and mental health issues[1-4]. The Intergovernmental Panel on Climate Change (IPCC) defines climate change as a long-term shift in the Earth's climate, which can be attributed to both natural processes and human activities that alter the atmosphere's composition. Without concerted efforts to mitigate climate change, the global mean surface temperature is projected to increase by 3.7°C to 4.8°C over the next century, leading to devastating health consequences. Air quality is intricately linked with climate change, as rising temperatures can increase the formation and concentration of air pollutants, exacerbating respiratory and cardiovascular diseases[5,6]. The health impacts of climate change are far-reaching, and it's essential to adopt a comprehensive approach that includes both mitigation and adaptation strategies to reduce greenhouse gas emissions and protect human health. By understanding the complex relationships between climate change, air quality, and human health, [7-9]we can develop effective policies and interventions to safeguard the well-being of individuals and communities worldwide

In areeas where substantial ozone depletion has occurred, results from a wide range of field studies suggest that increased UV-B radiation reduces terrestrial plant productivity by about 6%[10]. This reduction results from direct damage and increased diversion of plant resources towards protection and acclimation. Long-term effects of reduced plant growth could be important, particularly for potential carbon sequestration (capture). Changes in UV radiation caused by global environmental change can have very important consequences for terrestrial cosystems[11-15].

Fig. 1 World Health Organization’s Guideline Values for Air Pollutants

Region-specific changes in cloud cover and vegetative cover (in response to increased aridity or deforestation) predicted for the coming decades are likely to have large impacts on the levels of UV radiation received by terrestrial organisms[16-18].

These variations in UV radiation (both UV-B ad UV-A) will affect a large range of ecosystems. Predicted changes in climate may modify plant and ecosystem responses to UV radiation. For example, while moderate drought can decrease UV sensitivity in plants, further decreases in precipitation and increasing temperatures due to climate change are likely to restrict plant growth and compromise plants to re-distribute resources for protection from UV radiation and other climate factors[19,20]. Thus even limited climate change could have consequences for survival, especially in harsh environments. UV radiation promotes the breakdown of dead plant material and consequently carbon loss to the atmosphere. Exposure of vegetation and soils to UV radiation may increase in the future at low to mid-latitudes due to reduced cloud cover or more intensive land use.

By understanding the intricate relationships between climate change, air quality, and human health, policymakers, researchers and healthcare professionals can develop effective strategies to safeguard the well-being of individuals and communities worldwide[21-24]. Climate change disproportionately affects vulnerable populations, including older adults, working-age individuals and children, who face unique challenges in adapting to extreme weather conditions and environmental changes. Aging bodies respond differently to heat, with reduced ability to sweat, slower thirst response, and increased risk of heat-related illnesses like heat exhaustion and heat stroke. Chronic conditions like heart disease, diabetes and kidney issues can further exacerbate heat sensitivity. Effective interventions include risk-related education and government subsidies for residential cooling. Heat stress driven by climate change affects workers, particularly those in heavy physical labor, leading to reduced work intensity and increased risk of occupational illnesses and injuries[25-28]. Outdoor unorganized workers are especially vulnerable due to lack of workplace controls and limited access to resources. Exposure to air pollutants like particulate matter (PM2.5), nitrogen dioxide (NO2), and ozone can lead to adverse health effects, including reduced birth weight, preterm birth, gestational diabetes mellitus and childhood asthma. Maternal exposure to air pollution is a significant concern, with certain gestational periods being more susceptible to environmental stressors[29,30]

1)Climate Change Impact on Air Quality

Climate Change Impact on air quality is strongly coupled with weather and is therefore, sensitive to climate change. Meteorological variables such as humidity, wind speed and direction, temperature and mixing height (the vertical height of mixing in the atmosphere) play crucial roles in determining trends of air quality[31-33]. The air pollutant formation, chemical transformation, dilution, dispersion, trans port and deposition are highly dependent on these meteorological variables and cyclonic sys tems. Spickett et al stated that bushfires and heat waves can also influence air quality and may be affected by climate change. Higher temperature will cause more frequent droughts and higher possibility of fire danger. Many countries regulate their own air quality guidelines[34-38]. The World Health Organization Air Quality Guideline represents the most widely agreed and the latest assessment of health effects of air pollution (Fig 1).5 In this discussion, it covers 5 criteria of air pollutants namely particulate matter (PM), ozone (O3), nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon dioxide (CO2). PM is a mixture of solid particles and liquid droplets found in the air. Coarse particles are emitted from sources such as vehicles traveling on unpaved roads, crushing and grinding operations, material handling, and windblown dust, while fine particles may come from fuel combustion (motor vehi cles, power generation, industrial processes), wood stoves, and residential fireplaces[39-42]. The rela tionship between PM and the climate change is complex but can also be significant. Gases such as SO2, NO2, and volatile organic compounds can form fine particles in the atmosphere through chemical reactions involving atmospheric oxygen and water vapor. The formation of secondary particles also depends on solar radiation and relative humidity[43,44]. Particles in the atmosphere have a vital role in changing the solar radiation amount transmitted through the Earth's atmosphere. Sulfate particles will exert a direct effect by scattering incoming solar radiation back to space and causing a cooling effect. In contrast, black carbon particles absorb solar radiation and cause a warming effect. Wind speed and wind direction also have a significant impact on particle concentration[45].

The concentrations generally decrease by an order of magnitude between polluted regions and the diluting background air. An example is during the Southeast Asia Haze in 2005 whereby the PM10 reading in Malaysia and Thailand were 529 and 108 µg/m3, respectively, in the same month. The PM10 level dropped when the wind changed direction southwesterly to southeasterly, hence the air mass trajectory did not pass the forest-fire region. Particles also have an indirect effect on the size and number of cloud droplets which then causes more solar radiation to be reflected back to space, subsequently causing a cooling effect. However, the magnitude of the overall indirect effects of aerosols on climate is very uncertain. Atmospheric ozone (O3) is present in the stratospheric and tropospheric O3. The main envi ronmental concern is the tropospheric O3, also known as the ground-level O3[46]. It is highly depen dent on the temperature, sunlight and precursor levels such as nitrous oxides and volatile organic compounds. Research showed that ozone levels are higher in warmer seasons, and very high levels of ozone have been recorded during heat waves.12 Generally, temperature accelerates the photochemical reaction rate in the atmosphere and hastens the rate of tropospheric O3 formation; other hydroxyl radicals are also produced. O3 concentration also

depends on the wind speed[47,48]. Lower wind speed leads to reduced ventilation and causes higher formation of O3 and its precur sors, while increased water vapor will lower the potential for O3 formation. O3 concentration can be reduced by modifying factors that govern O3-producing reactions, for instance, the intensify ing hydrologic cycle will increase the number of cloudy days. More cloud cover in the morning could diminish reaction rates, and thus lower O3 formation[49].
Nitrogen oxides (NO2) and SO2 are emitted from high-temperature combustion processes, such as from power plants and automobiles. NO2 and SO2 oxidize in the atmosphere to form nitric acid and sulfuric acid, respectively. These acids can be deposited to the earth's surface in "wet" form as acid rain or in "dry" form as gases or aerosols. The wet deposition is determined by atmospheric chemistry and precipitation patterns. The amount, duration, location of precipitation and changes in the total acid levels play a vital role in the deposition. Factors that influence O3 formation will influence acid deposition[50-51]. The increase in temperatures will hasten the oxidation rates of SO2 and NOx to sulfuric and nitric acids, thus increasing the potential for acid deposition. Similar to O3, vigorous hydrologic cycle will increase the cloud cover and may reduce the rates of conversion from SO2 to acidic materials, thus lowering the potential for acid deposition.
The location of acid deposition is determined by the circulation and precipitation patterns that will transport the acidic materials. In urban areas, the most abundant pollutants are O3, NOx and particulate matter. SO2 is largely concentrated in industrial areas mainly due to coal combustion. Air pollutants can be generated by various sources such as motor vehicles, power plants, dry cleaners, factories, and even wind blown dusts and wildfires[52]. Because of the higher pollutant load, urban population is likely to be the primary group affected by air pollution

2) Health Impacts and Environmental Changes

Exposure to common air pollutants can have lasting effects on children's cognitive development and increase the risk of respiratory diseases, Extreme temperatures can cause heat-related illnesses, such as heat exhaustion and heat stroke, particularly among older adults and individuals with pre-existing medical conditions[53]. Climate change can lead to increased stress, anxiety, and trauma, disproportionately affecting vulnerable populations, including those with limited access to resources and healthcare.

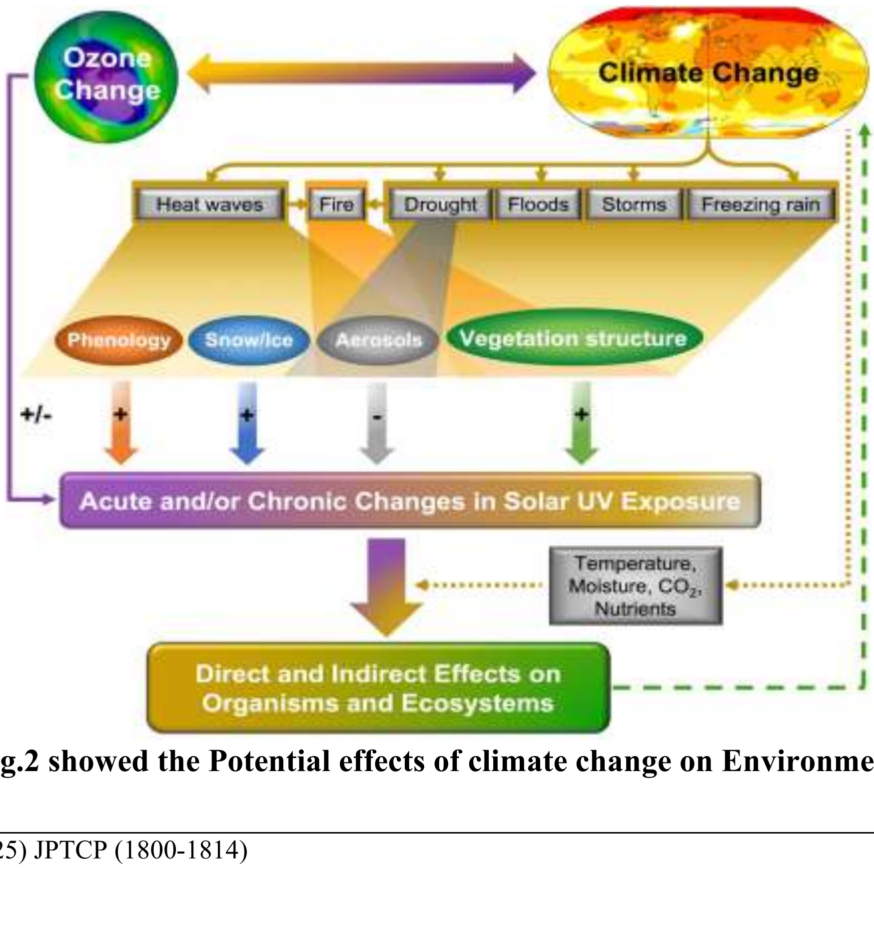

Fig.2 showed the Potential effects of climate change on Environment.

Studies emphasize the need for evidence-based research and interventions to drive comprehensive policies protecting vulnerable populations from climate-related health risks. Effective adaptation strategies include expanding access to cooling centers, improving public health messaging and ensuring medications and chronic conditions are considered in emergency planning[54]. Investing in renewable energy sources, advocating for conservation practices, and supporting carbon-neutral products can help mitigate the negative effects of climate change. Recent research has significantly advanced our understanding of the exposure and impact pathways through which climate variability and change affect human health.

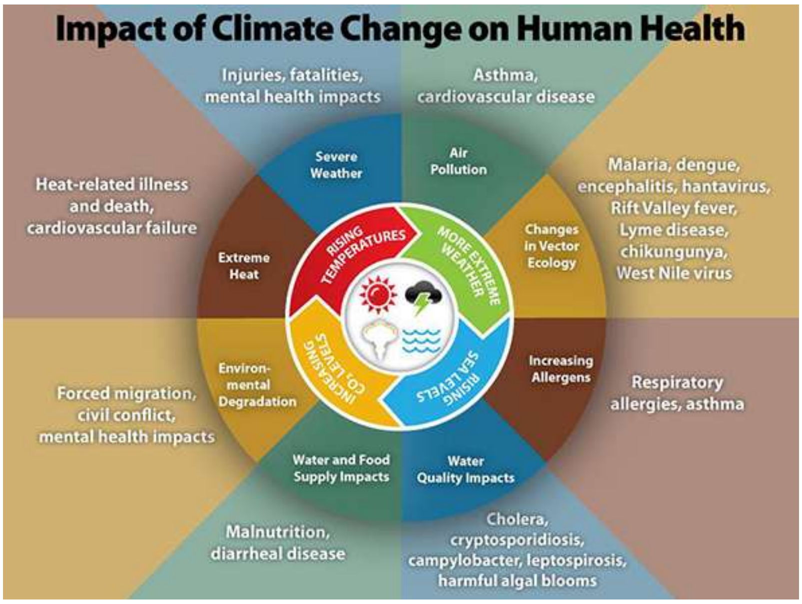

Fig. 3 showed the Potential effects of climate change on Human health

A key area of focus has been on quantifying the health risks associated with temperature extremes, particularly the cardiovascular impacts. Studies have shown that both hot and cold temperature anomalies can increase cardiovascular mortality risks, with females, older adults, and those with lower educational attainment being disproportionately affected. For instance, research in China found that cold temperatures increased the risk of ischemic stroke, while hot temperatures increased the risk of hemorrhagic stroke[55]. Furthermore, cold spells have been linked to a wide range of non-cardiovascular diseases, including respiratory, digestive, and mental health issues, with older adults and women facing the greatest risks.

Health risks of solar UV-B radiation can be assessed most confidently for cataracts and skin cancers. Although there is concern about an increased risk of infectious diseases, data to guide public health decisions are lacking. The incidences of cataract and skin cancers continue to rise in many countries, with significant societal impacts and costs to health care systems. In some regions the incidence of melanoma in children and young people is no longer increasing, or increasing incidence is confined to less lethal forms[56]. These changes probably reflect intensive public health information campaigns, based on sound research findings.

For infectious diseases, equivalent research findings are not available except from animal studies. Use of replacements for ozone depleting substances may result in risks to health but these have not been quantified. Health benefits of sun exposure are principally derived from vitamin D production in the skin following solar UV-B irradiation. Optimal vitamin D status supports bone health and may decrease the risk of several internal cancers and autoimmune, infectious and cardiovascular diseases. It is not yet clear whether oral vitamin D supplementation provides all of the benefits of UV-induced vitamin D or whether higher vitamin D status is always beneficial. Appropriate sun exposure to balance risk and benefits depends on personal The Environmental Effects Assessment Panel Report for 2010 xvi characteristics such as genetic background (including skin colour and vitamin D receptor types) and external/environmental factors (including diet, season, time of day

and latitude). This is an area of active current research, the results of which will provide guidance to the general public to better balance the benefits of sun exposure whilst minimizing risks.
Health effects associated with combined changes in solar UV radiation and climate are plausible; directed studies are required to guide health care decisions and future policies regarding health care. Higher temperatures are likely to lead to more skin cancers for the same exposure to UV radiation[57]. However, this is the most definitive statement that can be made to date about a combined effect, as more studies have not been done. Although higher temperatures may change sun exposure patterns, there is considerable uncertainty in modeling future human behaviour in response to climate change. There is enough information to suspect that combined effects could be serious, but the data to develop robust risk estimates are not available.
Scientifically and at political and policy levels, there are strong links between the depletion of ozone and climate change. However, addressing climate change is much more complicated than the phase-out of ODSs.There has been an increased focus on understanding physical interactions between ozone depletion and climate change. They can work in both directions: changes in ozone can induce changes in climate, and vice versa[58-60]. Changes in climate can also induce changes in UV radiation without affecting ozone. Thus, the return of ozone (or UV) to its value at any particular date in the past should not necessarily be interpreted as a recovery from the effects of ODSs.
The impacts of air pollution on human health and the environment will be directly influenced by future changes in climate, emissions of pollutants, and stratospheric ozone. Ultraviolet radiation is one of the controlling factors for the formation of photochemical smog which includes tropospheric ozone and aerosols; it also initiates the production of hydroxyl radicals, which control the amount of many climate- and ozone relevant gases in the atmosphere. Uncertainties still exist in quantifying the chemical processes and wind-driven transport of pollutants[61]. The net effects of future changes in UV radiation, meteorological conditions, and anthropogenic emissions may be large but will depend on local conditions, posing challenges for prediction and management of air quality. Numerical models predict that future changes in UV radiation and climate will modify the trends and geographic distribution of hydroxyl radicals, thus affecting urban and regional photochemical smog formation, as well as the abundance of several greenhouse gases. Concentrations of hydroxyl radicals are predicted to decrease globally by an average of 20% by 2100, with local concentrations varying by as much as a factor of two above and below current values[62,63].

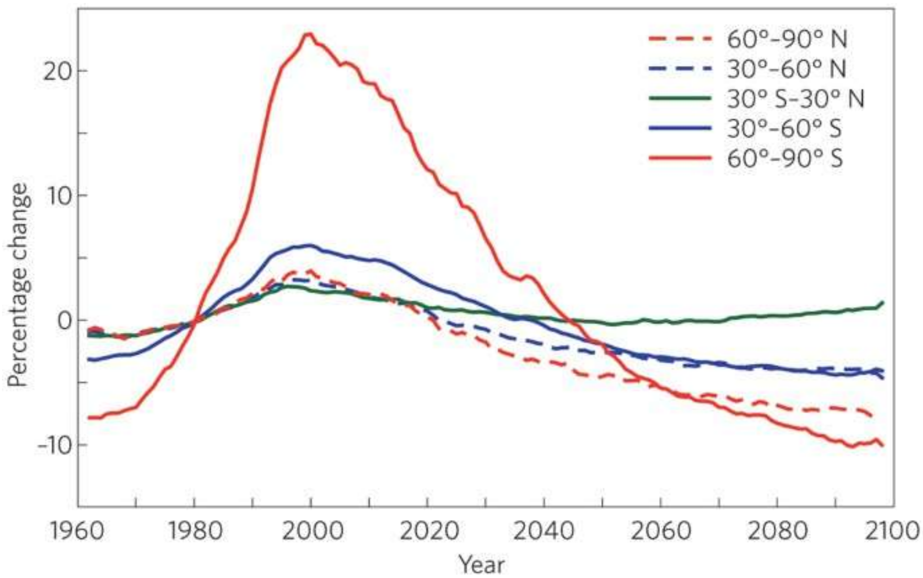

Fig. 4 showed the Trend of Ultraviolet radiations causing Climate change

However, significant differences between modelled and measured values in a limited number of case studies show that we do not fully understand the chemistry of hydroxyl radicals in the atmosphere. Therefore, the consequences for human health and the environment are uncertain.

Photochemically produced tropospheric ozone is projected to increase over the next 20 40 years in certain regions of low and middle latitudes because of interactions of emissions, chemical processes, and climate change. If emissions of anthropogenic air pollutants from combustion of fossil fuels, burning of biomass, and agricultural activities continue to increase, concentrations of tropospheric ozone will tend to increase. Climate driven increases in temperature and humidity will also increase tropospheric ozone production in polluted regions, but reduce it in more pristine regions[64]. Higher temperatures of some soils tend to increase emissions of nitrogen oxides (NOx) and biogenic volatile organic compounds leading to greater background concentrations of ozone in the troposphere. For the future protection of human health and the environment, more effective controls will need to be considered for emissions of NOx and VOCs related to human activities. Aerosols composed of organic substances have a major role for climate and air quality, and contribute a large uncertainty to the energy budget of the atmosphere. Aerosols are mostly formed via the UV-initiated oxidation of volatile organic compounds from anthropogenic and biogenic sources, although the details of the chemistry are still poorly known and current models under-predict their abundance[65]. A better understanding of their formation, chemical composition, and optical properties is required to assess their significance for air quality and to better quantify their direct and indirect radiative forcing of climate.

The decomposition of substitutes for ozone-depleting substances can lead to a range of chemical species, however with little relevance expected for human health and the environment. The hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) used as substitutes for ozone-depleting CFCs can break down into trifluoroacetic acid (TFA), which is very stable and will accumulate in the oceans, salt lakes, and playas.

The potential environmental impact of trifluoroacetic acid (TFA) and monofluoroacetic acid (MFA) has been assessed based on historical use and future projections. Despite the introduction of new products like fluoro-olefins, which may lead to increased loadings of TFA and MFA in environmental sinks, the overall risks to humans and aquatic organisms are expected to be negligible[66].

This conclusion is drawn from considering both the anthropogenic and natural sources of these compounds. Even when accounting for the cumulative amounts from both sources, the anticipated concentrations are not expected to pose significant risks[67]. The assessment suggests that the environmental impact of TFA and MFA will remain minimal, alleviating concerns about potential harm to human health and aquatic ecosystems

Addressing climate change and improving health requires a multi-faceted approach that involves both mitigation and adaptation strategies. Mitigation focuses on reducing greenhouse gas emissions to avoid the unmanageable impacts of climate change, while adaptation involves coping with the unavoidable effects[68].

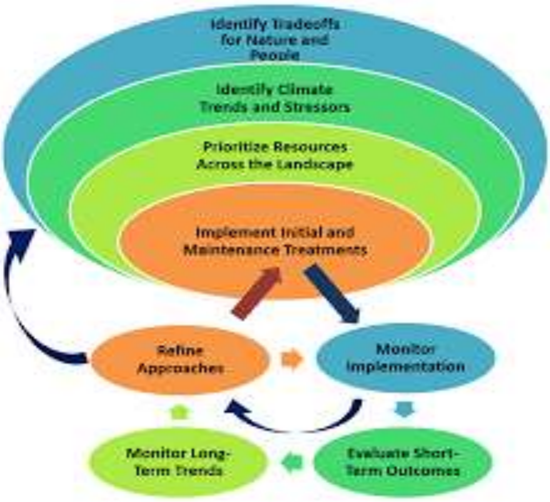

Fig. 5 Showed the Developing and Implementing Climate Change Adaptation

Transitioning to cleaner energy sources and reducing dependence on fossil fuels is a crucial aspect of mitigation. This shift can significantly improve health outcomes by minimizing exposure to air pollution, which is a major public health concern. Fossil fuel combustion releases harmful pollutants, including particulate matter, nitrogen oxides, and sulfur dioxide, contributing to respiratory and cardiovascular diseases. In contrast, cleaner energy sources like solar, wind, and hydroelectric power generate electricity without emitting these pollutants, thereby reducing the negative health impacts associated with air pollution[69]. By adopting cleaner energy sources, we can decrease the burden of air pollution-related health issues, improve overall air quality, and create healthier environments for communities worldwide

3)Challenges and Opportunities

A key challenge in addressing climate change is the lack of thorough knowledge on climate change vulnerabilities and adaptation options. This knowledge gap can hinder the development of effective adaptation strategies and limit the ability of communities to respond to climate-related impacts[70]. To overcome this challenge, effective communication with stakeholders and the public is crucial for supporting and participating in climate change programs. This includes raising awareness about climate change risks and adaptation options, as well as engaging stakeholders in the decision-making process.Participatory approaches from stakeholders, such as land use planners and infrastructure developers, can help identify areas where early adaptation is possible.Supporting institutional arrangements for linking federal, state, territory, and local responses can enhance the effectiveness of climate change programs[71].

4)Mitigation Strategies:

Mitigation strategies are essential for reducing the impacts of climate change. These strategies can be implemented in vari ous sectors, including

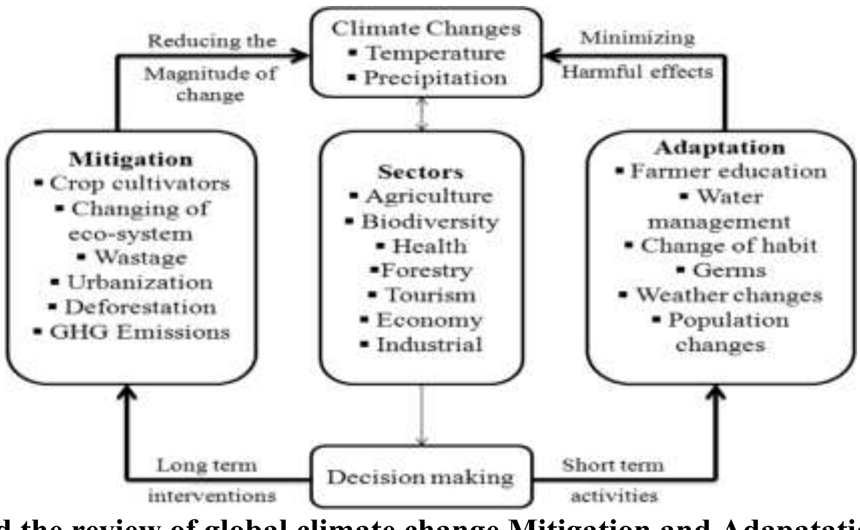

Fig. 6 showed the review of global climate change,Mitigation and Adapatation strategies.

energy, transportation, and land use. Some effective mitigation strategies include transitioning to renewable energy sources, improving energy efficiency, and promoting sustainable land use practices. For example, increasing the use of wind and solar power can significantly reduce greenhouse gas emissions, while sustainable land use practices like reforestation and agroforestry can help sequester carbon dioxide. Additionally, implementing policies like carbon pricing and emission standards can provide a financial incentive for companies and individuals to reduce their emissions[72]. By implementing these strategies, we can reduce the severity of climate change impacts and create a more sustainable future

Implementing standards like the Corporate Average Fuel Economy (CAFE) and LEED certification can reduce emissions, improve public health, and decrease energy consumption.Accelerating the adoption of renewable energy sources like solar, wind, and hydropower can significantly reduce

greenhouse gas emissions and improve air quality.Promoting sustainable deforestation practices, such as the UN's REDD program, and implementing agricultural policies that reduce emissions can contribute to a more sustainable future[73].
Climate change mitigation strategies are crucial for reducing the impacts of climate change. These strategies can be implemented in various sectors, including energy, transportation, and land use. Some effective mitigation strategies include transitioning to renewable energy sources, improving energy efficiency, and promoting sustainable land use practices. For example, increasing the use of wind and solar power can significantly reduce greenhouse gas emissions, while sustainable land use practices like reforestation and agroforestry can help sequester carbon dioxide[74,75]. By implementing these strategies, we can reduce the severity of climate change impacts and create a more sustainable future.

5)Adaptation Strategies:
In addition to these strategies, adaptation and mitigation efforts can be supported by international cooperation and knowledge sharing. Global initiatives and agreements, such as the Paris Agreement, can provide a framework for countries to work together to address the impacts of climate change. Furthermore, research and development of new technologies and practices can help identify effective solutions for reducing greenhouse gas emissions and adapting to climate change. By working together and sharing knowledge, we can develop and implement effective adaptation and mitigation strategies that support sustainable development and reduce the risks associated with climate change[76]. Investing in infrastructure that can withstand the impacts of climate change, such as sea-level rise and extreme weather events.

Some effective adaptation strategies which include building resilient infrastructure that can withstand the impacts of climate change, such as sea-level rise and extreme weather events.Restoring and preserving natural ecosystems that can provide protection against climate-related hazards, such as mangroves and wetlands.Implementing agricultural practices that are adapted to changing climate conditions, such as using drought-tolerant crops and conservation agriculture[77]. Developing early warning systems that can alert communities to potential climate-related hazards, such as floods and heatwaves.

To effectively address climate change, governments and international organizations should develop and implement policies that prioritize. Encouraging cooperation among different sectors and stakeholders to develop comprehensive climate plans.Integrating climate considerations into urban planning and infrastructure development to minimize vulnerability to climate-related disasters. Raising awareness about climate change causes, impacts, and mitigation strategies to promote individual and collective action.Sharing knowledge, technology, and resources across borders to amplify efforts to mitigate climate change impacts[78,79].By adopting a coordinated approach to climate change mitigation and adaptation, we can reduce the risks associated with climate-related disasters, promote sustainable development, and ensure a more resilient future for all.

Engaging local communities in the adaptation planning process and supporting community-based initiatives to build resilience. Enhancing public health systems to better respond to climate-related health issues, such as heat stress and vector-borne diseases[80].Encouraging sustainable practices, such as reducing energy consumption and using public transport, can contribute to both mitigation and adaptation efforts

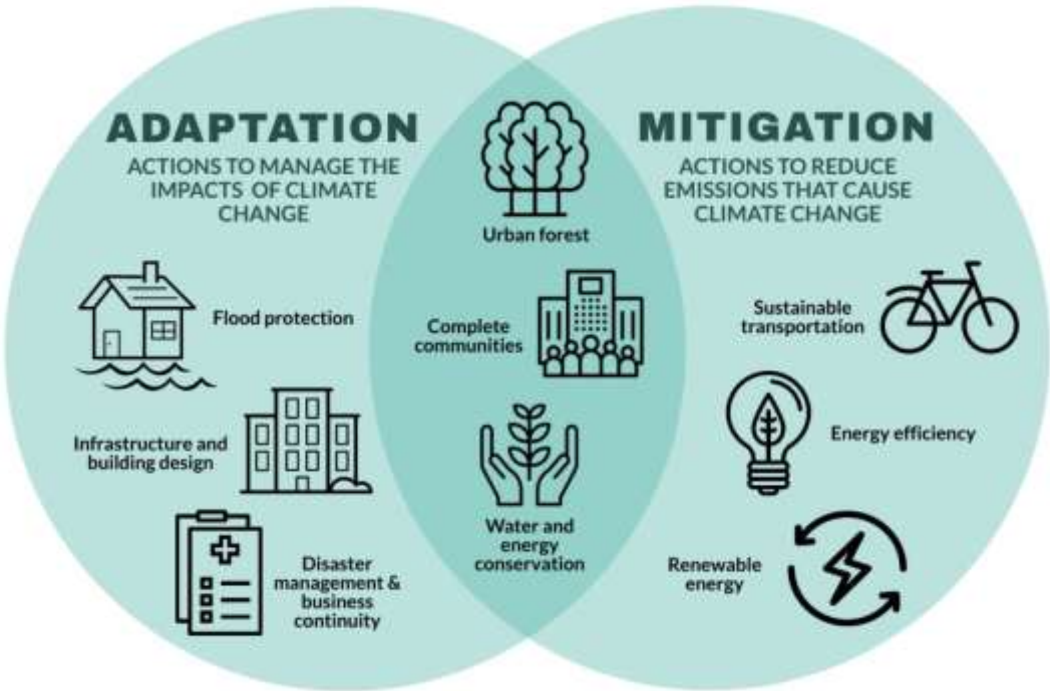

Fig. 7 showed the actions to manage impacts of Climate Change

METHODOLOGY

The original research articles were meticulously screened over a 10-year period, spanning from January 1, 2014, to December 31, 2024. To ensure a comprehensive review, multiple databases were utilized, including PubMed, Google Scholar and The Lancet, with a specific focus on articles written in English. The selection criteria were stringent, prioritizing articles that explicitly explored the complex interactions between climate change, air pollution, and health, with a particular emphasis on the health impacts experienced in urban areas. By carefully curating the literature based on these criteria, the review aimed to synthesize the most pertinent and insightful research on the topic, providing a robust foundation for understanding the multifaceted relationships between climate change, air quality and human health in urban contexts.

Research Gaps and Priorities

There is a need for more robust analytic approaches to quantify exposure-response relationships and explore associations between changing weather patterns and exposure to indoor aeroallergens. More research is needed in low- and middle-income countries to better understand the health impacts of climate change and air pollution in these contexts. Integrated and intensive health services and environmental interventions can help mitigate the health impacts of climate-related disasters

CONCLUSION

Recent research highlights the critical need to address the interconnected challenges of climate change and air pollution, emphasizing that health considerations provide a compelling argument for policy action. Improving environmental and human health can be a synergistic process, but certain societal groups, such as children, pregnant mothers and the elderly are particularly at risk from exposure to climate change and air pollution. To effectively address these challenges, it is essential to develop a robust understanding of the complex linkages between air quality and climate change. This includes identifying new impact pathways, ensuring accurate information on the interaction between climate change, air pollution, human health and developing improved monitoring and forecasting systems. Furthermore, collaboration between governments, international organizations, healthcare professionals, researchers and communities is crucial for making meaningful progress. By establishing policy frameworks grounded in sound scientific evidence and promoting proactive measures, such as adaptation and mitigation strategies, we can work towards minimizing the negative effects of climate-related events and strengthening communities. Ultimately, addressing the complex relationship between climate change and human health requires a concerted effort and unwavering attention to protect vulnerable populations and ensure the safety of public health

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research

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