Impacts of Climate Change on Occupational Health and Safety: A Comprehensive Review

John A. Jia [a*] and Njideka I. Jia [a]

[a] *Center for Occupational Health, Safety and Environment, Faculty of Engineering, University of Port Harcourt, Choba, Nigeria.*

Authors' contributions

This work was carried out in collaboration between both authors. Author JAJ designed the review and wrote the first draft of the manuscript. Author NIJ provided additional screening of the literature. Both authors read and approved the final manuscript.

Review Article

ABSTRACT

Climate change, a continual variation in weather condition orchestrated by human activities is no longer a distant threat. Its impacts are increasingly evident across the globe, affecting various aspects of human life. Among the myriad consequences of climate change, its implications for occupational health and safety are significant but often overlooked. This paper provides a comprehensive review of the impacts of climate change on occupational health and safety, examining the direct and indirect effects on workers across different sectors. By synthesizing current research and empirical evidence, this paper highlights the urgent need for proactive measures to mitigate risks and protect workers in the face of a changing climate. The mitigation measures include investing in prevention, preparedness, and resilience-building measures, use of personal protective equipment (PPE), workplace modifications, and emergency response plans.

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*Corresponding author: Email: aseerjia@yahoo.com;

Others are capacity building, training, and awareness-raising initiatives for employers, workers, and occupational health professionals, strengthened collaboration and partnerships between government agencies, employers, workers' organizations, and other stakeholders among others.

Keywords: Climate change; occupational health; safety; extreme weather; occupational risks.

1. INTRODUCTION

Climate change refers to significant and long-term alterations in temperature, precipitation patterns, sea levels, and other climatic variables, primarily driven by human activities such as burning fossil fuels, deforestation, and industrial processes. It is one of the worst crises faced by humans in this era and the World Health organization (WHO) describes it as "the biggest risk global health faces in this century" [1]. It has caused various environmental changes including desertification, heat waves, deglaciation, melting permafrost wildfires, storms, droughts and extinction of some animal species [2]. Consequently, people now experience more flooding, extreme heat, scarcity of food and water, new disease outbreaks and economic loss leading to significant human migration and conflict [3].

The United Nations have defined climate change as "long term shifts in temperature and weather patterns" [4]. Although temperature and weather changes can occur unprovoked, human activities have been its major cause since the 1800s [4] and illustrated in Fig. 1. According to the IPCC [5], greenhouse gas emissions from human activities are the major cause of climate change. If urgent action is not taken to curb climate change, the ecosystem will experience more disasters in future. The 2015 Paris agreement resolved to ensure warming doesn't exceed 2°C but according to UNEP [6], warming is still expected to reach 2.7^{o}C by the end of the century [6].

The major features of climate change include prolonged temperature changes, precipitation, pressure and humidity changes in the environment that elicits retreat of global ice sheets and elevated sea level. As a result of climate change, environmental problems such as drought, flooding, severe fires, storms and decline in biodiversity now abound [4]. There is overwhelming evidence of 0.2^{o}C rise in surface temperatures per decade [7] and it was reported that global warming reached 1.2^{o}C above the pre-industrial era by 2020 with warmer days and nights [8].

Occupational health and safety (OHS) is a multidisciplinary field concerned with protecting the health, safety, and well-being of workers in various industries and workplaces. Ensuring OHS is vital for safeguarding workers from occupational hazards, preventing work-related injuries and illnesses, and promoting a safe and healthy work environment [10]. According to the WHO, "occupational health deals with all aspects of health and safety in the workplace and has a strong focus on primary prevention of hazards" [11].
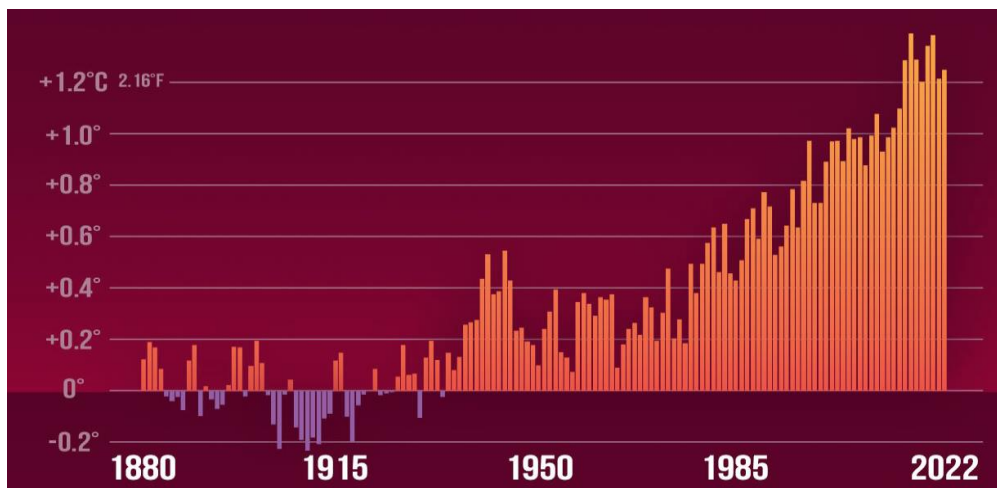
Fig. 1. Global variation in average temperature since the 1880s [9]

The aim of occupational health is to promote and maintain the highest degree of physical, mental and social well-being of workers in all occupations; to prevent departures from health caused by working conditions among workers; protect workers in their employment from risks resulting from factors adverse to health; the placing and maintenance of the worker in an occupational environment adapted to his physiological and psychological capabilities and in summary, the adaptation of work to man and of each man to his job [12].

According to the official estimates of the United Nations and the WHO/ILO Joint Estimate of the Work-related Burden of Disease and Injury, about 2 million people die yearly due to exposure to occupational risk factors [13]. Globally, above 2.78 million people die yearly due to workplace-related accidents or diseases, equating to one death every fifteen seconds. Additionally, 374 million non-fatal work-related injuries occur annually. The economic burden of occupational-related injury and death is nearly four per cent of the global gross domestic product each year. The human cost of this adversity is huge [14]. Workplace incidents and occupational diseases can be prevented by implementing occupational safety and health programs at company level [15,16].

Climate change is primarily driven by the following:

Greenhouse gas emissions which has the ability to absorb and release radiant energy within the thermal infrared range, producing greenhouse effect which makes life on earth possible [7] because they absorb part of the heat coming from the sun, thereby slowing down the rate of heat escape into space and keeping the earth warm [17]. Naturally occurring greenhouse gases such as water vapour and clouds are responsible for about 75% of the greenhouse effect by causing an increase in global temperature and their increase depends on temperature. Other greenhouse gases such as Carbon dioxide, ozone, Chlorofluorocarbon and nitrous oxide do not depend on temperature but still exert similar beneficial effect as the naturally occurring ones [17] as illustrated in Fig. 2.

The rise in anthropological activities since the beginning of the industrial revolution has led to the significant increase in greenhouse gases, thus creating a massive radiative imbalance. Carbon dioxide produced from human activities contributes most to global warming. There has been rises in carbon dioxide and methane concentrations since 1750 by 48% and 160% respectively. Increase in carbon dioxide production emanates from fossil fuels combustion in cars, industries, agricultural production, home and electricity generation [18] while methane emission emanates from livestock, manure, waste water, etc [19].

Agricultural activities lead to the creation of more land for agriculture, mainly through deforestation. Land for agricultural activities currently occupies about 34% of the earth's land area and this is achieved through deforestation. The felling of trees though deforestation leads to the release of carbon dioxide contained in trees and means less trees are available to absorb carbon dioxide [2]. Forests can reduce the impact of high temperatures [20], therefore constant reduction of forests contributes to global warming. **Industrial Processes and Emissions** release GHGs and other pollutants into the atmosphere. Also, emissions of CO_2, methane, nitrous oxide, and fluorinated gases from industrial sources contribute to climate change and air pollution [21]. **Transportation and Energy Production** contribute majorly to CO_2 emissions and air pollutants. Energy production from coal, oil, and natural gas accounts for a significant portion of global GHG emissions [22]. **Aerosols and Clouds** which are tiny solid or liquid substances suspended in the air may be produced naturally or as a result of human actions and greatly contributes to climate change by scattering and absorbing solar radiation. Aerosols produced by dust, pollution and burning of fossil fuels reduce the amount of sunlight getting to the earth [23].

Feedback Mechanisms and Amplifying Effects: Climate change triggers feedback mechanisms that amplify its effects, such as the melting of polar ice caps, release of methane from permafrost, and changes in ocean circulation patterns. These feedback loops can accelerate global warming and lead to more severe climate impacts [5]. It is necessary to understand the drivers of climate change in order to formulate effective mitigation and adaptation strategies to address its impacts on ecosystems, economies, and societies worldwide. By reducing greenhouse gas emissions, promoting sustainable land use practices, and transitioning to clean energy sources, humanity can mitigate the severity of climate change and build a more resilient future for current and future generations.
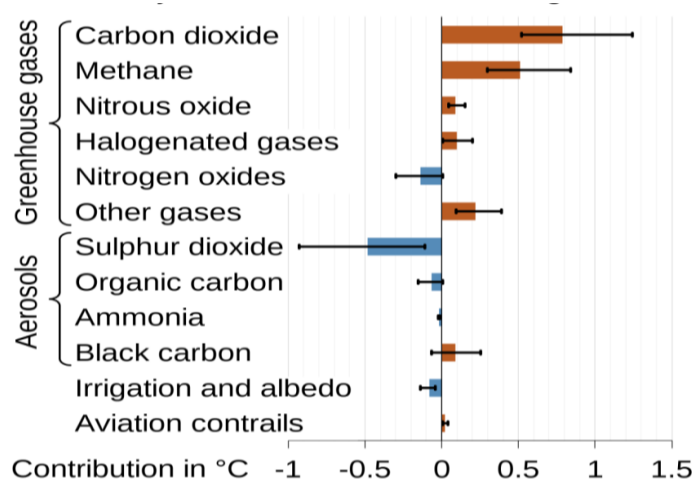
Fig. 2. Greenhouse gases as causes of climate change [19]

Understanding the implications of climate change on workers' health and safety is therefore essential for the following reasons:

i. **Worker Vulnerability and Occupational Hazards.** Workers across various sectors, including agriculture, construction, manufacturing, transportation, and healthcare, are vulnerable to climate-related hazards such as heat waves, extreme weather events, air pollution, and vector-borne diseases. Climate change amplifies existing occupational risks and introduces new challenges, posing threats to workers' physical and mental well-being. By studying the impacts of climate change on workers' health and safety, researchers and policymakers can identify specific hazards, assess risk factors, and develop targeted interventions to protect workers [24].

ii. **Public Health and Economic Implications.** Work-related injuries, illnesses, and fatalities associated with climate-related hazards impose significant public health and economic burdens [25]. Healthcare costs, productivity losses, and absenteeism resulting from heat stress, respiratory illnesses, injuries, and mental health issues contribute to the economic burden of climate change on workers and employers. Therefore, understanding the health and economic consequences of climate-related occupational risks is crucial for informing decision-making, resource allocation, and policy development aimed at reducing vulnerabilities and enhancing resilience.

iii. **Legal and Regulatory Frameworks.** Governments, international organizations, and regulatory agencies have a responsibility to protect workers' health and safety and ensure compliance with occupational health and safety regulations. Knowing that climate change worsens occupational hazards and health risks, there is a rising need to integrate climate resilience into existing legal and regulatory frameworks. Research on the impacts of climate change on workers' health and safety provides evidence-based support for strengthening regulations, updating standards, and implementing adaptive measures to address emerging challenges [26].

iv. **Social Equity and Justice**. Climate change disproportionately affects marginalized and vulnerable populations, including low-income workers, migrant workers, indigenous communities, and informal sector workers. Inequities in exposure to climate-related hazards, access to resources, and socio-economic vulnerabilities worsen disparities in occupational health outcomes. Therefore, studying the link between climate change, occupational health and social equity highlights the importance of addressing structural inequalities, promoting inclusive policies, and empowering marginalized workers to mitigate risks and adapt to changing environmental conditions [27].

v. **Preventive Strategies and Adaptation Measures.** Proactive measures to protect workers from climate-related hazards require a deep understanding of the

complex interactions between environmental factors, occupational exposures, and health outcomes. Research on the impacts of climate change on workers' health and safety informs the development and implementation of preventive strategies, risk assessment tools, early warning systems, and adaptation measures tailored to specific industries, occupations, and geographic regions. By investing in research and evidence-based interventions, stakeholders can enhance preparedness, resilience, and sustainability in the face of climate change, ultimately safeguarding workers' health and well-being [28].

Studying the impacts of climate change on workers' health and safety is therefore crucial for mitigating risks, protecting vulnerable populations, promoting social justice, and building climate-resilient workplaces. By addressing these challenges comprehensively, stakeholders can foster healthier, safer, and more sustainable working environments for all.

2. CLIMATE CHANGE AND EXTREME WEATHER EVENTS

2.1 Increasing Frequency and Intensity of Heat Waves, Storms, Floods, and Wildfires

Climate change has led to a noticeable increase in the frequency and intensity of various extreme weather events worldwide such as escalating occurrences of heat waves, storms, floods, and wildfires.

i. **Heat waves:** Heat waves, defined as prolonged periods of excessively hot weather, have become more frequent and severe due to rising global temperatures. Studies indicate an increase in the frequency, duration, and intensity of heat waves in many regions, leading to elevated health risks, heat-related illnesses, and [8].

ii. **Storms:** Climate change has contributed to the intensification of tropical storms, hurricanes, cyclones, and typhoons, characterized by stronger winds, heavier rainfall, and higher storm surges. Research suggests that warming ocean temperatures fuel the development of more powerful and destructive storms, posing risks to coastal communities, infrastructure, and ecosystems [29].

iii. **Floods:** Changes in precipitation patterns, increased rainfall intensity, and rising sea levels have heightened the risk of flooding in many regions, both coastal and inland. Urbanization, deforestation, and inadequate infrastructure exacerbate flood hazards, leading to property damage, displacement of populations, and loss of lives [2].

iv. **Wildfires:** Climate change has been linked to the increased incidence and severity of wildfires fueled by higher temperatures, prolonged droughts, and altered vegetation patterns. Changes in precipitation regimes and the expansion of fire-prone landscapes contribute to the spread of wildfires, posing threats to ecosystems, biodiversity, and human communities [30].

The increasing frequency and intensity of heatwaves, storms, floods, and wildfires underscore the urgent need for climate action, adaptation measures, and resilience-building efforts at local, national, and global scales. Addressing the root causes of climate change and implementing strategies to mitigate risks are essential for protecting communities, ecosystems, and economies from the escalating impacts of extreme weather events.

3. WORKPLACE HAZARDS

Various types of workplace hazards can damage the health and safety of people at work. These include Physical hazards, biological hazards, chemical hazards and psychosocial hazards among others [31]. The use of personal protective equipment can be used to protect against many of these hazards [32]. A study conducted by the World Health Organization and the International Labour Organization revealed that exposure to long working hours is the occupational risk factor linked with the greatest disease burden of about 745,000 fatalities from ischemic heart disease and stroke events in 2016 [33]. Overwork is therefore the globally leading occupational health risk factor [13].

i. **Physical hazards** are common in the workplace. Occupational hearing loss is a common type of physical hazard. Falls are also common, especially in construction, extraction, transportation, healthcare, and building cleaning and maintenance [34]. Also, the moving parts of machines,

sharp edges, hot surfaces and other hazards can crush, burn, cut, shear, stab or wound workers if used unsafely [34].

ii. **Biological hazards (biohazards)** include infectious microorganisms such as viruses, bacteria and toxins produced by those microorganisms. Biohazards may affect workers in hospitals. Outdoor workers, including farmers, landscapers, and construction workers are also at risk of exposure to numerous biohazards, including animal bites and stings. Health care workers, including veterinary health workers are also at risk of exposure to blood-borne pathogens and various infectious diseases, especially emerging diseases [35].

iii. **Chemical hazards** from dangerous chemicals can pose a hazard in the workplace. Hazardous chemicals, include neurotoxins, immune agents, dermatologic agents, carcinogens, reproductive toxins, systemic toxins, asthmagens, pneumoconiotic agents, and sensitizers [36]. There are occupational exposure limits set by authorities to mitigate the risk of chemical hazards.

iv. **Psychosocial hazards** include risks to the mental and emotional well-being of workers, such as feelings of job insecurity, long work hours, and poor work-life balance. Research has shown that psychological abuse is present within the workplace. A study by Gary Namie on workplace emotional abuse found that 31% of women and 21% of men who reported workplace emotional abuse exhibited three key symptoms of post-traumatic stress disorder (hypervigilance, intrusive imagery, and avoidance behaviors). Sexual harassment is another serious hazard found in workplaces.

Occupational health and safety is therefore important for the following reasons:

i. **Worker Protection and Health Promotion:** Occupational Health and Safety (OHS) measures aim to protect workers from workplace hazards, including physical, chemical, biological and psychosocial risks. By implementing safety protocols, providing personal protective equipment (PPE), and conducting risk assessments, employers can mitigate occupational health risks and prevent work-related injuries and illnesses [37].

ii. **Legal and Ethical Obligations:** Governments worldwide have established regulations and standards to ensure workplace safety and protect the rights of workers. Employers have a legal and ethical responsibility to provide a safe working environment, comply with OHS laws and regulations, and address hazards promptly [38].

iii. **Productivity and Economic Impact:** Investing in occupational health and safety enhances productivity, reduces absenteeism, and lowers healthcare costs for businesses. Work-related injuries, illnesses, and accidents can result in lost productivity, increased insurance premiums, and legal liabilities, affecting overall business performance and profitability [38].

iv. **Worker Empowerment and Engagement:** Engaging workers in OHS initiatives promotes a culture of safety, encourages active participation in hazard identification and risk management, and fosters a sense of responsibility for one's own and colleagues' well-being. Empowered workers are more likely to adhere to safety protocols, report hazards, and collaborate with employers to improve workplace safety [39].

v. **Public Health and Social Justice:** Occupational health and safety are integral components of public health and social justice, ensuring that all workers, regardless of occupation or industry, have the right to a safe and healthy work environment. Addressing occupational hazards and inequalities in OHS promotes social equity, reduces disparities in occupational health outcomes, and contributes to sustainable development [4].

vi. **Long-Term Sustainability and Well-Being:** Prioritizing OHS is essential for achieving long-term sustainability and preserving the health and well-being of current and future generations of workers. Sustainable workplaces prioritize health and safety, environmental stewardship, and social responsibility, recognizing the interconnectedness of human health, ecological health, and economic prosperity.

Recognizing the importance of occupational health and safety and adopting proactive measures to protect workers, employers, governments, and stakeholders can create safer,

healthier, and more sustainable workplaces that promote individual well-being and contribute to overall societal progress.

4. EFFECTS OF CLIMATE CHANGE ON OUTDOOR WORKERS EXPOSED TO EXTREME TEMPERATURES, AIR POLLUTION, AND PHYSICAL HAZARDS

4.1 Impacts

Outdoor workers, including those in agriculture, construction, landscaping, and emergency response, are particularly vulnerable to the impacts of climate change due to their prolonged exposure to environmental conditions. These impacts include extreme temperatures, air pollution, and physical hazards.

i. **Extreme Temperatures:** Climate change worsens heat waves and extreme heat events, exposing outdoor workers to dangerously high temperatures. Prolonged exposure to heat stress can lead to heat-related illnesses such as heat exhaustion, heatstroke, and dehydration among outdoor workers. Studies have documented increased incidence of heat-related injuries and fatalities among agricultural workers, construction workers, and others laboring outdoors during heat waves [40].

ii. **Air Pollution:** Climate change contributes to poor air quality through the exacerbation of smog, ground-level ozone, and particulate matter pollution. Outdoor workers, especially those in urban areas and industrial sites, are exposed to elevated levels of air pollutants, which can worsen respiratory conditions, such as asthma and chronic obstructive pulmonary disease (COPD). Long-term exposure to air pollution increases the risk of cardiovascular diseases, respiratory illnesses, and premature mortality among outdoor workers [41].

iii. **Health Impacts of Ozone (O$_3$):** Ozone is a reactive gas formed by the photochemical reaction of volatile organic compounds (VOCs) and nitrogen oxides (NOx) in the presence of sunlight. Prolonged exposure to elevated ozone levels can cause respiratory irritation, exacerbate pre-existing lung conditions (e.g., asthma, chronic obstructive pulmonary disease), and impair lung function. Outdoor workers, such as construction workers, landscapers, and agricultural workers, are at increased risk of ozone exposure due to their activities in open environments during peak ozone hours [42].

iv. **Health Impacts of Particulate Matter (PM):** Particulate matter consists of tiny particles suspended in the air, categorized based on size into PM10 (coarse particles) and PM2.5 (fine particles). Inhalation of particulate matter can penetrate deep into the respiratory system, causing or exacerbating respiratory and cardiovascular diseases, including bronchitis, heart attacks, and strokes. Outdoor workers exposed to high levels of particulate matter, such as those working in construction, mining, and traffic-related occupations, face increased risks of respiratory illnesses and cardiovascular events [43,44].

v. **Physical Hazards:** Climate change influences the frequency and severity of physical hazards encountered by outdoor workers, including extreme weather events, falling debris, slippery surfaces, and hazardous terrain. Increased frequency of storms, floods, and wildfires poses risks to workers involved in emergency response, disaster recovery, and infrastructure repair and maintenance. Occupational injuries, including falls, lacerations, crush injuries, and electrocutions, may occur during extreme weather conditions and natural disasters [45].

4.2 Adaptive Measures

To protect outdoor workers from the adverse effects of climate change, employers can implement various adaptive measures, including:

i. Provision of adequate hydration stations and rest breaks during hot weather.

ii. Supplying appropriate personal protective equipment (PPE), such as lightweight and breathable clothing, hats, and sunscreen.

iii. Implementing heat stress management programs, training workers on recognizing heat-related illnesses, and establishing protocols for emergency response.

iv. Monitoring air quality levels and implementing measures to reduce exposure to harmful pollutants, such as adjusting work schedules and providing respiratory protection.

v. Conducting hazard assessments and implementing engineering controls and administrative controls to mitigate physical hazards associated with extreme weather events and environmental conditions [40].

Outdoor workers play a crucial role in various sectors of the economy, but they face unique occupational health and safety challenges exacerbated by climate change. By implementing proactive measures and adaptive strategies, employers, policymakers, and stakeholders can minimize risks and protect the health and well-being of outdoor workers in the face of changing environmental conditions.

4.3 Challenges for Emergency Responders and Disaster Recovery Workers

Emergency responders and disaster recovery workers play crucial roles in curbing the impacts of natural and man-made disasters, including hurricanes, floods, wildfires, earthquakes, industrial accidents, and public health emergencies. However, they face numerous challenges exacerbated by climate change. These challenges include:

i. **Increased Frequency and Severity of Disasters:** Climate change has led to the increased frequency, intensity, and unpredictability of extreme weather events and natural disasters. Emergency responders and disaster recovery workers are faced with more frequent deployments and prolonged periods of emergency response and recovery operations. The strain on resources, personnel, and infrastructure has worsened the challenges of coordinating effective emergency responses and providing timely assistance to affected communities [8].

ii. **Health and Safety Risks:** Emergency responders and disaster recovery workers are exposed to various physical, chemical, biological, and psychological hazards during rescue, recovery, and cleanup operations. Extreme heat, poor air quality, contaminated water, hazardous materials, unstable structures, and infectious diseases pose risks to the health and safety of workers. Also, climate-related hazards such as heatwaves, wildfires, and floods increase the likelihood of heat-related illnesses, respiratory problems, injuries, and mental health issues among responders and recovery workers [40].

iii. **Infrastructure Damage and Access Constraints:** Climate-related disasters often result in widespread damage to critical infrastructure, including roads, bridges, power lines, and communication networks. Limited access to disaster-affected areas due to road closures, debris blockages, and unsafe conditions complicates the deployment of emergency response teams and the delivery of essential services and supplies. Recovery efforts may also be hindered by logistical challenges, resource constraints, and the need for specialized equipment and expertise to address complex infrastructure damage [45].

iv. **Community Vulnerability and Resilience:** Vulnerable populations, including low-income communities, elderly individuals, children, and people with disabilities, are disproportionately affected by climate-related disasters. Emergency responders and disaster recovery workers face the challenge of addressing the specific needs and vulnerabilities of diverse communities, including language barriers, cultural sensitivities, and access to healthcare and social support services. Therefore, strengthening community resilience, promoting equitable recovery, and fostering collaboration with local stakeholders are essential for building adaptive capacity and reducing vulnerabilities to climate-related hazards [46].

v. **Training and Capacity Building:** Effective emergency response and disaster recovery require specialized training, skills, and competencies tailored to the challenges of climate change. Investing in training programs, exercises, and capacity-building initiatives can enhance the preparedness, response capabilities, and resilience of emergency responders and recovery workers. Collaboration between government agencies, non-governmental organizations (NGOs), academic institutions, and the private sector is essential for sharing knowledge, best practices, and lessons learned in disaster management and climate adaptation [1].

Addressing the challenges faced by emergency responders and disaster recovery workers in the area of climate change requires comprehensive strategies that integrate risk reduction,

preparedness, response, recovery, and resilience-building efforts. By prioritizing worker safety, community well-being, and climate adaptation measures, stakeholders can enhance the effectiveness and sustainability of disaster management systems in an increasingly volatile and uncertain climate.

4.4 Challenges for Outdoor Workers

Outdoor workers are exposed to varying levels of ozone and particulate matter depending on factors such as geographical location, weather conditions, and proximity to pollution sources. Work activities that involve physical exertion, such as heavy lifting, digging, and operating machinery, can increase the inhalation rate and uptake of air pollutants among outdoor workers. Lack of access to personal protective equipment (PPE), inadequate training on air pollution risks, and limited awareness of preventive measures can increase the vulnerability of outdoor workers to ozone and particulate matter pollution [47].

4.5 Mitigation Strategies

Employers can implement various strategies to mitigate air pollution exposure and protect outdoor workers' health, including:

i. Modifying work schedules to minimize outdoor activities during periods of high ozone and particulate matter concentrations, such as midday and early afternoon.
ii. Providing respiratory protection, such as N95 respirators, to outdoor workers in areas with elevated levels of air pollutants.
iii. Promoting engineering controls, such as ventilation systems and dust suppression measures, to reduce on-site emissions and exposure to particulate matter.
iv. Educating workers about the health risks associated with ozone and particulate matter pollution, training them on proper use of PPE, and encouraging adherence to preventive measures [48].

Addressing the health impacts of elevated ozone and particulate matter levels on outdoor workers requires a multifaceted approach involving collaboration between employers, government agencies, healthcare professionals, and workers' representatives. By implementing preventive measures, raising awareness, and advocating for clean air policies, stakeholders can protect the respiratory health and well-being of outdoor workers in the face of air pollution challenges.

5. RESPIRATORY ILLNESSES AND EXACERBATION OF PRE-EXISTING CONDITIONS AMONG OUTDOOR AND INDOOR WORKERS

Respiratory illnesses, including exacerbation of pre-existing conditions, are significant health concerns for both outdoor and indoor workers due to exposure to various environmental pollutants and occupational hazards [49].

5.1 Outdoor Workers

Air Pollution Exposure: Outdoor workers, such as construction workers, agricultural workers, and traffic controllers, are exposed to elevated levels of air pollutants such as particulate matter, ozone, nitrogen oxides, and volatile organic compounds. Prolonged exposure to these pollutants can lead to respiratory irritation, exacerbation of asthma and other respiratory conditions, reduced lung function, and increased susceptibility to respiratory infections.

Particulate Matter and Ozone: Particulate matter (PM) and ozone (O_3) are particularly harmful pollutants for outdoor workers. PM can penetrate deep into the lungs, causing inflammation, exacerbating respiratory diseases, and increasing the risk of cardiovascular problems. Ozone, a reactive gas formed by pollutants in sunlight, can irritate the respiratory tract, leading to coughing, throat irritation, and exacerbation of asthma symptoms.

Exacerbation of Pre-existing Conditions: Outdoor workers with pre-existing respiratory conditions such as asthma, chronic bronchitis, or chronic obstructive pulmonary disease (COPD) are at higher risk of experiencing worsening of their symptoms due to exposure to air pollutants and occupational hazards. Work-related activities that involve physical exertion or exposure to dust, fumes, or allergens can further exacerbate respiratory symptoms in susceptible individuals [49].

5.2 Indoor Workers

Indoor Air Quality: Indoor workers, including office workers, healthcare workers, and factory workers, may be exposed to indoor air pollutants such as volatile organic compounds (VOCs), formaldehyde, mold spores, and allergens from dust mites or pets. Poor indoor air quality, inadequate ventilation, and exposure to indoor pollutants can contribute to respiratory

symptoms, allergic reactions, and respiratory infections among indoor workers.

Occupational Exposures: Certain occupations involve exposure to specific respiratory hazards indoors, such as healthcare workers exposed to airborne pathogens, cleaning staff exposed to cleaning chemicals, and factory workers exposed to dust, fumes, or chemical vapors. Occupational asthma, rhinitis, and other respiratory conditions can result from prolonged exposure to these occupational hazards, particularly in poorly ventilated or inadequately controlled work environments.

Sick Building Syndrome: Indoor workers may also experience respiratory symptoms and discomfort associated with sick building syndrome (SBS), characterized by a range of non-specific symptoms such as coughing, wheezing, throat irritation, and fatigue. Contributing factors to SBS include poor indoor air quality, inadequate ventilation, high humidity levels, and presence of indoor pollutants, which can affect the respiratory health and well-being of indoor workers [49].

Both outdoor and indoor workers are susceptible to respiratory illnesses and exacerbation of pre-existing conditions due to exposure to environmental pollutants, occupational hazards, and poor indoor air quality. Implementing measures to improve air quality, enhance ventilation, minimize exposure to respiratory hazards, and provide respiratory protection can help protect the respiratory health of workers in diverse occupational settings.

6. VECTOR-BORNE DISEASES AND OCCUPATIONAL RISKS

6.1 Expansion of Vector Habitats and Transmission Zones Due to Warmer Temperatures and Changing Precipitation Patterns

Climate change, characterized by rising temperatures and altered precipitation patterns, is facilitating the expansion of habitats for vectors such as mosquitoes, ticks, and other disease-carrying organisms. The implications of climate change on vector-borne diseases and the expansion of transmission zones include the following:

i. **Warmer Temperatures and Vector Biology:** Warmer temperatures can accelerate the development and reproduction rates of vectors, leading to increased population sizes and extended active seasons. Mosquitoes, for example, thrive in warmer climates, with higher temperatures promoting faster breeding cycles and shorter development times for pathogens within vectors [7].

ii. **Altered Precipitation Patterns and Habitat Expansion:** Changes in precipitation patterns, including increased rainfall or drought conditions, can create favorable environments for vector breeding and survival. Standing water, resulting from heavy rainfall or flooding, provides breeding sites for mosquitoes, while droughts can concentrate vector populations around limited water sources [50].

iii. **Expansion of Transmission Zones:** As vectors adapt to changing climatic conditions, they may expand their geographical ranges into previously unaffected areas. Transmission zones for vector-borne diseases, such as malaria, dengue fever, Zika virus, Lyme disease, and West Nile virus, may shift poleward or to higher elevations as temperatures become more conducive to vector survival [51].

iv. **Ecological Disruptions and Disease Dynamics:** Climate change-induced habitat alterations can disrupt ecological balances and lead to changes in vector-host interactions, pathogen transmission dynamics, and disease emergence. Deforestation, urbanization, and land use changes may further exacerbate vector proliferation and disease transmission by altering natural habitats and increasing human-vector contact [52].

6.2 Risks of Vector-Borne Diseases such as Malaria, Dengue Fever, Lyme Disease, and Zika Virus for Outdoor Workers

Outdoor workers, including agricultural workers, construction workers, landscapers, and forestry workers, are at increased risk of exposure to vector-borne diseases due to their prolonged outdoor activities in environments where vectors thrive.

i. **Malaria:** Outdoor workers in regions where malaria is endemic face the risk of mosquito bites, particularly during dusk

and dawn when Anopheles mosquitoes, the vectors of malaria, are most active. Prolonged exposure to outdoor environments, such as agricultural fields or construction sites, increases the likelihood of mosquito bites and transmission of the malaria parasite (*Plasmodium spp.*) [53].

ii. **Dengue Fever:** Outdoor workers in urban and peri-urban areas are at risk of dengue fever transmitted by Aedes mosquitoes, which breed in stagnant water containers found in construction sites, discarded tires, and other debris. Dengue outbreaks can occur in areas with inadequate sanitation and water management, leading to increased mosquito breeding sites and higher transmission rates among outdoor workers [54].

iii. **Lyme Disease:** Outdoor workers, such as forestry workers, landscapers, and park rangers, are at risk of Lyme disease transmitted by black-legged ticks (Ixodes scapularis) infected with the bacterium *Borrelia burgdorferi*. Exposure to tick-infested habitats, such as wooded areas, grasslands, and brushy vegetation, increases the likelihood of tick bites and transmission of Lyme disease spirochetes [55].

iv. **Zika Virus:** Outdoor workers in tropical and subtropical regions are at risk of Zika virus transmitted primarily by Aedes mosquitoes, which breed in standing water sources commonly found in outdoor work environments. Zika virus infection during pregnancy can lead to congenital Zika syndrome in infants, highlighting the importance of preventing mosquito bites among pregnant outdoor workers [37].

6.3 Challenges for Healthcare Workers in Diagnosis, Treatment, and Prevention of Vector-borne Illnesses

Healthcare workers play a crucial role in diagnosing, treating, and preventing vector-borne illnesses. However, they face several challenges due to the complex nature of these diseases, including varying clinical presentations, limited diagnostic tools, emerging drug resistance, and changing vector distribution patterns.

Diverse Clinical Presentations: Vector-borne diseases often present with a wide range of clinical symptoms, making diagnosis challenging for healthcare workers. Symptoms may overlap with other common febrile illnesses, leading to misdiagnosis or delayed treatment initiation [56].

Limited Diagnostic Tools: Diagnostic tests for vector-borne diseases may be limited in availability, specificity, and sensitivity, particularly in resource-limited settings. Serological tests, polymerase chain reaction (PCR), and antigen detection assays may require specialized laboratory facilities and trained personnel, posing logistical challenges for diagnosis [57].

Emerging Drug Resistance: Increasing resistance to antimalarial, antibacterial, and antiviral drugs poses significant challenges for the treatment of vector-borne diseases. Healthcare workers must stay updated on current treatment guidelines and surveillance data to adapt treatment regimens and combat drug-resistant strains effectively [58].

Changing Vector Distribution Patterns: Climate change and environmental factors influence the distribution, abundance, and behavior of disease vectors, leading to shifts in transmission patterns and geographic spread. Healthcare workers must be aware of changing vector distribution patterns and associated disease risks to provide timely diagnosis, treatment, and prevention advice [59].

Health System Capacity and Surveillance: Weak health systems in endemic regions may lack the infrastructure, resources, and trained personnel needed to effectively diagnose, treat, and prevent vector-borne diseases. Strengthening health system capacity, investing in laboratory infrastructure, and enhancing disease surveillance are essential for improving healthcare delivery and response to vector-borne illnesses [60].

6.4 Integrated Prevention Strategies

Implementing integrated vector management (IVM) strategies, including vector surveillance, larval source reduction, insecticide application, and personal protective measures, can help mitigate the risks of vector-borne diseases for outdoor workers. Providing training on vector-borne disease prevention, distributing insect repellents, wearing protective clothing, and scheduling outdoor activities to avoid peak mosquito activity hours are essential preventive measures [61].

Outdoor workers play a critical role in various industries but face heightened risks of exposure to vector-borne diseases due to their occupational activities. By raising awareness,

implementing preventive measures, and integrating vector control efforts into occupational health and safety programs, employers and public health authorities can protect the health and well-being of outdoor workers and reduce the burden of vector-borne diseases in affected communities.

6.5 Mitigation and Adaptation Strategies

Effective surveillance, vector control measures, and public health interventions are essential for mitigating the impacts of climate change on vector-borne diseases. Integrated vector management strategies, including habitat modification, larval source reduction, insecticide use, and community engagement, can help reduce vector populations and disease transmission risks [62].

Addressing the expansion of vector habitats and transmission zones due to warmer temperatures and changing precipitation patterns requires a multi-disciplinary approach involving collaboration between public health authorities, researchers, policymakers, and communities. By implementing proactive measures and adaptive strategies, stakeholders can mitigate the impacts of climate change on vector-borne diseases and safeguard public health.

6.6 Community Engagement and Education

Healthcare workers play a critical role in community engagement, health promotion, and education on vector-borne disease prevention measures, including personal protective measures, vector control strategies, and environmental management. Collaborating with communities, local authorities, and non-governmental organizations can enhance community resilience and empower individuals to take proactive steps in preventing vector-borne illnesses [61].

Addressing the challenges faced by healthcare workers in the diagnosis, treatment, and prevention of vector-borne illnesses requires a comprehensive approach that encompasses capacity building, research, surveillance, and community engagement. By strengthening healthcare systems, improving diagnostic capabilities, and promoting evidence-based interventions, stakeholders can enhance the effectiveness of vector-borne disease control efforts and reduce the burden of these diseases on affected populations.

7. ADAPTATION STRATEGIES AND POLICY RESPONSES

7.1 Integration of Climate Resilience into Occupational Health and Safety Regulations and Standards

The integration of climate resilience into occupational health and safety (OHS) regulations and standards is crucial for addressing the emerging risks and challenges posed by climate change in the workplace. Climate resilience can be integrated into OHS regulations and standards by:

i. **Assessment of Climate Risks:** OHS regulations can require employers to conduct comprehensive assessments of climate-related risks in the workplace, including extreme heat, wildfires, storms, flooding, and air pollution. These assessments should consider the potential impacts of climate change on worker health and safety and identify measures to mitigate risks and enhance resilience [63].

ii. **Incorporation of Adaptation Measures:** OHS standards can mandate the incorporation of adaptation measures to address climate-related hazards and ensure worker protection. This may include implementing heat stress management programs, providing adequate personal protective equipment (PPE), enhancing emergency preparedness and response plans, and promoting worker training and education on climate resilience [64].

iii. **Integration of Green Jobs and Sustainable Practices:** OHS regulations can promote the integration of green jobs and sustainable practices that contribute to climate resilience in the workplace. This may involve incentivizing the adoption of renewable energy technologies, promoting energy efficiency measures, and encouraging sustainable transportation options to reduce greenhouse gas emissions and promote environmental sustainability [40].

iv. **Enhanced Monitoring and Reporting:** OHS regulations can require enhanced monitoring and reporting of climate-related health and safety risks, incidents, and outcomes in the workplace. This data can inform decision-making processes, facilitate early detection of emerging risks, and support the development of targeted interventions to protect workers from climate-related hazards [65].

v. **Strengthened Collaboration and Partnerships:** OHS regulations can encourage strengthened collaboration and partnerships between government agencies, employers, workers' organizations, and other stakeholders to address climate resilience in the workplace. This may involve sharing best practices, exchanging knowledge and expertise, and coordinating efforts to develop and implement effective climate adaptation strategies [66].

By integrating climate resilience into OHS regulations and standards, policymakers can enhance the protection of workers from climate-related hazards, promote sustainable and resilient workplaces, and contribute to global efforts to mitigate and adapt to climate change. These efforts are essential for safeguarding worker health and safety in a changing climate.

7.2 Implementation of Heat Stress Management Programs, Personal Protective Equipment (PPE), and Workplace Modifications

The implementation of heat stress management programs, personal protective equipment (PPE), and workplace modifications is essential for protecting workers from the adverse effects of heat-related illnesses and injuries, particularly in the context of climate change. These measures can be effectively implemented in workplaces by doing the following:

i. **Heat Stress Management Programs:** Heat stress management programs aim to identify, assess, and control heat-related hazards in the workplace to protect workers from heat-related illnesses such as heat exhaustion and heat stroke. These programs typically include risk assessments, heat exposure monitoring, heat stress training for workers and supervisors, acclimatization protocols, hydration strategies, rest breaks in shaded or cool areas, and emergency response procedures.

ii. **Personal Protective Equipment (PPE):** Personal protective equipment, such as lightweight, breathable clothing, wide-brimmed hats, cooling vests, and cooling bandanas, can help mitigate heat stress and protect workers from excessive heat exposure. Employers should provide appropriate PPE based on the level of heat exposure and the specific tasks performed by workers. PPE should be comfortable, fit properly, and allow for adequate ventilation to prevent overheating [67].

iii. **Workplace Modifications:** Workplace modifications involve engineering controls, administrative controls, and environmental changes to reduce heat exposure and create a safer and more comfortable work environment for employees. Examples of workplace modifications include installing ventilation systems, providing shaded rest areas, using reflective materials to reduce heat absorption, scheduling outdoor work during cooler times of the day, and implementing heat mitigation measures such as misting systems or fans [68].

iv. **Training and Education:** Training and education are essential components of heat stress management programs, ensuring that workers and supervisors are aware of the risks associated with heat exposure and understand how to prevent heat-related illnesses and injuries. Training should cover topics such as recognizing the signs and symptoms of heat stress, proper hydration practices, the importance of acclimatization, the use of PPE, and emergency response procedures [69].

v. **Monitoring and Evaluation:** Regular monitoring and evaluation of heat stress management programs are essential to assess their effectiveness, identify areas for improvement, and ensure compliance with OHS regulations and standards. Employers should monitor environmental conditions, heat stress indicators (e.g., body temperature, heart rate), and worker feedback to evaluate the success of interventions and make necessary adjustments to protect worker health and safety [64].

By implementing comprehensive heat stress management programs, providing appropriate PPE, making workplace modifications, and ensuring adequate training and education, employers can effectively protect workers from heat-related hazards and create safer and more resilient workplaces in the face of climate change. These measures are essential for safeguarding worker health and well-being in environments with elevated temperatures and increasing heat exposure.

Table 1. Summary of impacts of climate change on different sectors and mitigations

Sector	Impacts	Mitigations Suggested
Agriculture	Extreme temperatures and heat stress affect crop yields, livestock, and worker health.	Provision of hydration, PPE (hats, sunscreen), rest breaks, heat stress management programs.
Construction	Increased frequency of heatwaves and air pollution lead to higher risks of heat-related illnesses and injuries.	Adapt work schedules to avoid heat peaks, provide respiratory protection, train workers on heat and air pollution risks.
Landscaping	Exposure to ozone, particulate matter, and extreme weather conditions like storms.	Modify work schedules, provide respiratory protection (N95 respirators), use engineering controls to reduce emissions.
Emergency Response	Increased disaster frequency and intensity (storms, floods, wildfires), health and safety risks during operations.	Provide PPE, invest in training and capacity-building, and address community vulnerabilities with resilient strategies.
Mining	Air pollution and heat stress affect worker health, exacerbating respiratory illnesses.	Implement dust suppression measures, provide ventilation systems, and respiratory protection.
Healthcare	Increased exposure to biological hazards from emerging infectious diseases due to changing climates.	Strengthen healthcare worker training and improve access to PPE.
Industrial	Increased risks of exposure to air pollutants (smog, ozone, particulate matter) and physical hazards.	Monitor air quality, provide respiratory protection, and adjust work activities to avoid peak pollution times.
Disaster Recovery	Physical hazards from damaged infrastructure and environmental conditions during extreme weather events.	Conduct hazard assessments, use engineering controls, and ensure adequate logistical support for recovery operations.
Outdoor Workers (e.g., Construction, Agriculture)	Exposure to air pollution (PM, ozone), exacerbation of pre-existing respiratory conditions, reduced lung function, respiratory infections.	Improve air quality, enhance ventilation, minimize exposure to hazards, provide respiratory protection.
Indoor Workers (e.g., Offices, Factories)	Exposure to indoor air pollutants (VOCs, formaldehyde, mold), respiratory symptoms, sick building syndrome.	Improve indoor air quality, enhance ventilation, control humidity, minimize exposure to pollutants, provide respiratory protection.
Outdoor Workers (Agriculture, Forestry)	Increased risk of vector-borne diseases (malaria, dengue, Zika, Lyme disease) due to expanded vector habitats.	Implement integrated vector management (IVM), personal protective measures, insect repellents, schedule outdoor work to avoid peak mosquito activity.
Healthcare Workers	Challenges in diagnosing and treating vector-borne diseases due to changing vector distribution patterns and drug resistance.	Strengthen health systems, improve diagnostic tools, enhance vector-borne disease surveillance, provide training on prevention and treatment.
All Sectors (General)	Heat-related illnesses (heat exhaustion, heat stroke), reduced productivity, mental health challenges.	Heat stress management programs, PPE (cooling vests, breathable clothing), workplace modifications (shaded areas, ventilation systems), training and

Sector	Impacts	Mitigations Suggested
		education.
Vector-Borne Diseases Sector	Expansion of vector habitats, ecological disruptions, increased risk of diseases (malaria, dengue, Lyme disease).	Habitat modification, larval source reduction, insecticide use, community engagement, integrated vector management strategies.
Policy and Regulation	New OHS risks due to climate change, increased worker vulnerability.	Integrate climate resilience into OHS regulations, require climate risk assessments, promote green jobs and sustainable practices, enhance monitoring and reporting.
Low-Income and Marginalized Workers	Higher vulnerability to climate hazards due to systemic inequalities.	Capacity building, resilience-building measures, strengthened collaboration between stakeholders, policies to address inequalities.

8. SUMMARY OF IMPACTS OF CLIMATE CHANGE ON VARIOUS SECTORS AND MITIGATIONS

The summary of occupational health and safety impacts discussed in this review paper are documented in Table 1 below. The table shows individual sectors, nature of the impacts and mitigations suggested to manage the impacts and prevent escalations.

9. CONCLUSION

The review has shown that climate change exacerbates environmental hazards and disasters, leading to increased risks of heat waves, storms, floods, wildfires, air pollution, and vector-borne diseases, which pose significant threats to worker health and safety. It has also revealed that certain groups, including low-income workers, migrants, indigenous communities, and marginalized populations, are disproportionately affected by climate change due to systemic inequalities, lack of access to resources, and exposure to hazardous working conditions. The review further revealed that climate-related hazards contribute to heat-related illnesses, respiratory diseases, vector-borne diseases, injuries, and mental health disorders among workers, leading to increased absenteeism, reduced productivity, and economic losses. Investing in prevention, preparedness, and resilience-building measures, such as heat stress management programs, PPE, workplace modifications, and emergency response plans, is essential for mitigating climate-related risks and enhancing worker protection. In addition, capacity building, training, and awareness-raising initiatives are critical for employers, workers, and occupational health professionals to enhance their knowledge, skills, and awareness of climate-related hazards, preventive measures, and emergency protocols.

Also, strengthened collaboration and partnerships between government agencies, employers, workers' organizations, and other stakeholders are essential for developing and implementing effective climate resilience strategies, sharing best practices, and fostering a culture of safety and well-being in the workplace.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the editing of manuscript.

Details of the AI usage is given below:

1. ChatGPT, 4omini has been used to summarize the manuscript into the Table 1 in Section 8.0 following reviewer comment. Input prompt was "From the article (1) Tabulate the sectors affected by climate change (2) impacts on the sector and (3) mitigations suggested."

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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