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Influence of climate change on emerging pathogens and human immunity

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Abstract

Global warming can be defined as the detectable increase in average global temperature in the last ten years regarding frequency and intensity. Climate change represents a long-term detectable climatic variability. The climatic system of the earth is disrupted because of the continuous production of greenhouse gases, which raises the risk of the emergence and re-emergence of human pathogens. In this review, we aimed to present the different mechanisms of climate change that increase human/pathogen exposure, introduce the recent concept of disaster microbiology, and discuss the effects of climate change on zoonoses as well as the effects of climate change on antibiotic resistance and human health.

Keywords: Climate change, Emerging Pathogens, Immunity, Global warming, Greenhouse gases

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Introduction

The utmost threats facing humanity in the twenty-first century are “climate change and global warming” according to the World Health Organization.[1] Global warming can be defined as the detectable increase in average frequency and intensity of global temperature in the last ten years.[2] Climate change represents a long-term detectable climatic variability that may lead to short-term hazards known as extreme weather events affecting their frequency or distribution such as droughts, heat waves, excessive rainfall, floods, dust storms, typhoons, hurricanes, and wildfires.[3] According to the intergovernmental panel on climate change (The United Nations body for evaluating the science linked to climate change), the increase in temperature globally is expected to be faster and may range between +1.4 and 4.4 °C by the termination of the 21st century.[1] The climatic system of the earth is disrupted because of the continuous production of greenhouse gases, which raises the risk for the emergence and re-emergence of human pathogens.[4] Emerging pathogens include novel unidentified diseases and former diseases that mutated or evolved from a previously known pathogen and acquired new characteristics such as a new geographic distribution or a new epidemiological existence, it was reported that the main emerging human pathogens are zoonotic.[5]

Another challenge the world is facing due to climate change is the presence of enough effective antibiotics against bacterial infections. Studies showed that there is a direct link between climate change and antibiotic resistance.[6,7] Health is hugely affected by climate change leading to the reduction of the ability of the human body to cope with various infections.[4] In this review, we aimed to present the different mechanisms of climate change that resulted in increased human/pathogen exposure, introduce the recent concept of disaster microbiology, and discuss the effects of climate change on zoonoses as well as the effects of climate change on antibiotic resistance and human health.

Methods

Electronic databases including PubMed/Midline, Web of Science, and Google Scholar were searched for case reports and series, case-control, cohort, and cross-sectional studies, as well as reviews from the inception of the database to June 2023. The inclusion criteria included studies written in English and relevant to our objectives, without any restrictions regarding time, and/or population category. The search was carried out by two independent authors. The search was performed by using terms related to "Climate Change " AND " Infection" OR "Climate change" AND "Human immunity " OR "Immunity". Extreme weather events such as droughts, heat waves, excessive rainfall, floods, dust storms, typhoons, hurricanes, and wildfires were considered. Infections including zoonoses and the occurrence of antibiotic resistance were also deliberated.

Climate Change Mechanisms Lead to Increased Human/Pathogen Exposure

1. Climate Hazards

Climate change and its related events have led to 12.6 million deaths worldwide in 2012 as was reported by the World Health Organization [8]. This emphasizes the critical of investigating the impact of climate change on emerging pathogens and human immunity (Table 1). Greenhouse gases disrupt the equilibrium between the produced infrared radiation and the introduced solar radiation thus accumulating in the atmosphere and causing elevation of temperatures. Warming fastens the evaporation of water in soil, causing drought which can cause heatwaves. Excess heatwaves and drought favor the situation for wildfires. Excess evaporation increases precipitation, which leads to floods as rain falls in excess. Elevated water temperatures of the oceans increase storms' strength, further augmented by the rise of sea levels, which leads to floods. Carbon dioxide (CO2) uptake in the oceans increases the acidity of the water, also alterations directions of water currents in oceans, and elevated temperatures decrease oxygen concentration in seawater. Deforestation is considered a direct producer of greenhouse gases[7] (Figure 1).

Human health is not the only issue raised by the phenomenon of climate change; it is also a matter of social injustice where marginalized groups of low socioeconomic populations are facing the utmost risks of the adverse effects of climate change with minimal contribution to greenhouse gas production (the richest 10% of the earth inhabitants are accountable for 52% of all carbon production) this phenomenon is known as “Environmental injustice” [9] Environmental injustice is directly associated with the phenomenon of “Microbial injustice” which is demarcated as the unequal exposure to infections and the hazards faced by deprived societies.[10]

A known example of the environmental effects of climate change is the irregular variations in the equatorial Pacific Ocean atmospheric pressure as well as surface temperature recognized as the El Niño-Southern Oscillation. It is formed of two stages the warming stage (El Niño) as well as the cooling stage (La Niña), which leads to life-threatening weather events such as tornadoes, hurricanes, heat waves, floods, and drought.[11]

Table 1. An Overview of The Impact of Climate Change on Human Immunity and Emerging Pathogens.

Impacts of Climate Change	
Climate Change Mechanisms Lead to Increased Human/ Pathogen Exposure	1. Climate Hazards 1.1. Climate hazards brought pathogens closer to humans. 1.2. Climate hazards brought humans closer to pathogens. 1.3. Climate hazards increase the strength of pathogens.
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Impacts of Climate Change on Zoonoses	1. Vector-borne zoonoses 1.1 Mosquito-borne zoonotic diseases 1.1 A. Malaria 1.1.B. Dengue 1.1.C. Chikungunya 1.1.D. Japanese Encephalitis 1.1.E. Rift Valley Fever 1.1. F. West Nile Fever 1.1. G. Yellow Fever 1.1.H. Zika Fever 1.2 Sand fly-borne zoonoses 1.3 Tick-borne zoonoses 1.4 Other vector-borne diseases
	2. Waterborne zoonoses
	3. Foodborne zoonoses
	4. Rodent-borne zoonoses
	5. Airborne zoonoses
Impacts of Climate Change on Antibiotic Resistance	1. Elevated temperature and antibiotic resistance
	2. Floods and antibiotic resistance
	3. Drought and antibiotic resistance
Impacts of Climate Change on Human Immunity	1. Nutrition 2. Gut Microbiome 3. Diseases and Infections

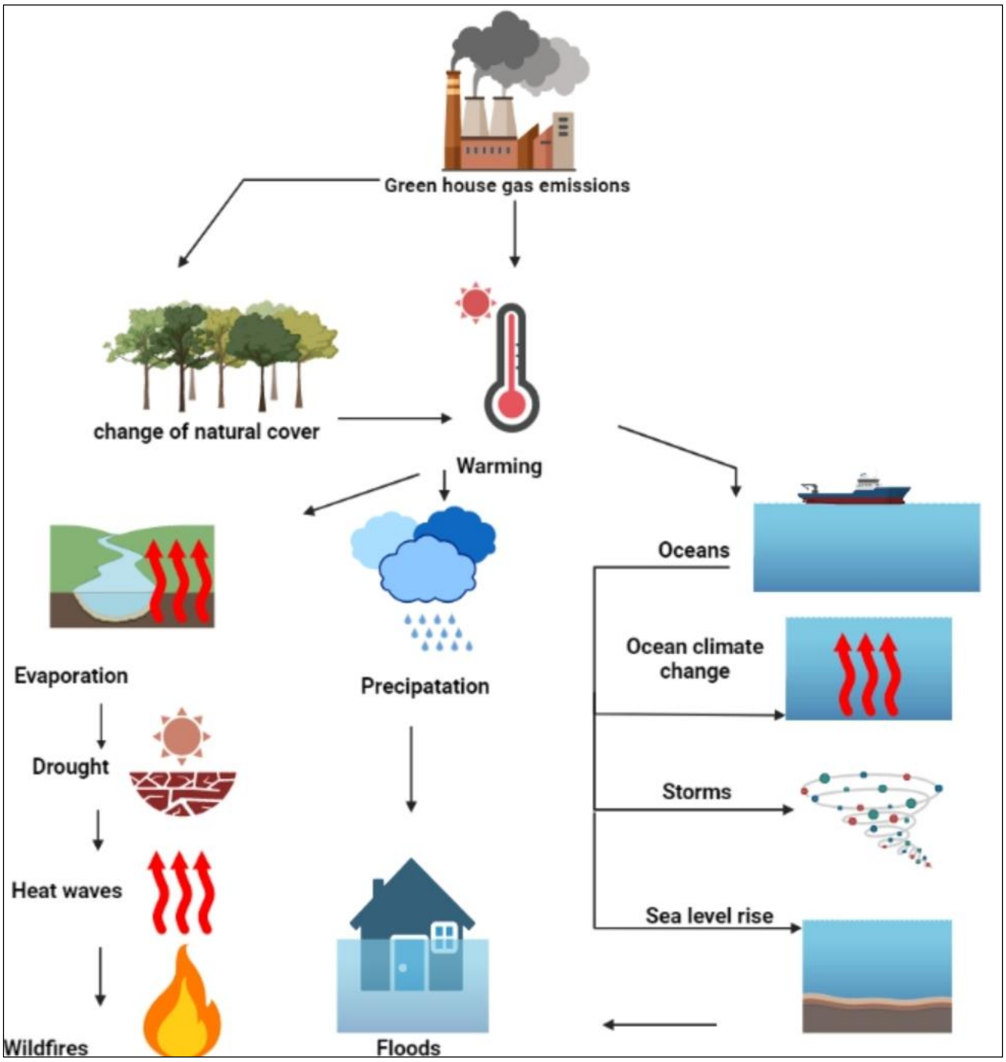

Figure 1. Climate change and its hazardous effects on the Earth system.

1.1. Climate hazards brought pathogens closer to humans

Several consequences occurred due to climate hazards which brought pathogens closer to people. Geographical migration of species due to unfavorable climate shifts as warming and precipitation has led to the spread of vectors such as birds, mosquitoes, fleas, ticks, and different animals. The wide spread of different vectors and hosts was responsible for a lot of bacterial, viral, and protozoal outbreaks [4]. Elevated temperatures of aquatic systems were associated with cases of *Vibrio* species. [8]

Disruptions of wildlife habitat by extreme events such as wildfire and floods caused viral spillovers from bats, rodents, and primates where they came closer to man to search for food and new habitat.[12] Global rise of temperature occurs near the poles of the earth more than at the equator which has caused the melting of ice caps. This phenomenon will not only cause drowning and disappearance of cities but will also expose long-frozen pathogens as was previously reported during an outbreak of anthrax in the Arctic region in 2016.[13]

1.2. Climate hazards brought humans closer to pathogens

On the other hand, climate change also brought humans closer to pathogens. For example, recreational water-related activities are blooming due to heat waves which were reported to cause many waterborne-related illnesses such as gastroenteritis and Vibrio spp. associated infections.[4]

Human displacement due to floods and sea level rise was associated with cases of cholera, typhoid, hepatitis, Legionnaires disease, salmonellosis, and shigellosis.[14] Human encroachment into wildlife due to urbanization brought humans closer to vectors and pathogens causing several outbreaks such as Ebola, Lyme disease, and malaria. Other disease outbreaks were reported because of the movement of livestock to areas with better grassland to avoid drought and heavy precipitation such as anthrax and hemorrhagic fever.[15]

Human social gatherings are affected by extreme weather events such as heavy rains and elevated temperatures. Social gatherings play a key role in the transmission of viral infections such as the coronavirus disease of 2019 (COVID-19) with an increased risk in poorly ventilated spaces.[16]

1.3. Climate hazards increase the strength of pathogens

The strengths of pathogens were augmented by enhanced weather appropriateness for reproduction, faster life cycles, longer seasons of exposure, increasing pathogen vector encounters such as shorter incubation periods, and amplified virulence.[4] Rise in temperatures increased the expansion of the mosquito populations, endurance, biting frequency, and viral reproduction elevating West Nile virus transmission.[17]

Warmer oceans helped the blooming of pathogenic algae and their diseases. Elevated water temperatures of oceans associated with heavy rains decrease coastal water salinity and help favorable conditions for *Vibrio vulnificus* (a wound infection) as well as *Vibrio cholerae*, this clarifies the occurrence of Vibrio outbreaks in new areas.[18] Moreover, the rise of temperatures and heavy rains augmented food and habitat availability, helping boom rodent populations and the rise of cases of plague and hantaviruses.[4]

Stagnant water due to storms, heavy rainfall, and floods increased reproduction places and growing areas for mosquitoes and the range of microorganisms that they carry (e.g., leishmania, malaria, Rift Valley fever, yellow fever, Saint Louis encephalitis, dengue, and West Nile fever).[19]

The virulence of various pathogens is increased by climatic hazards. Upregulation of gene expression of proteins due to heat caused *Vibrio* species to show increased transmission, adhesion, dissemination, and survival leading to more aggressive host injury.[18]

2. Disaster Microbiology

Recently, the American Society for Microbiology introduced a new term “Disaster microbiology” and defined it as a scope of research that focuses on the microorganisms' effects occurring due to strong storms and natural catastrophes.[10]

Disaster microbiology could help public health researchers and organizations involved in preparations for disasters by providing information on microbes and their outbreaks dependent on the type of disaster and geography as well as socioeconomic conditions.[9]

2.1. Natural Disasters

Natural disasters are directly involved with public health issues, including those linked to communicable diseases. Cyclones, tsunamis, flooding, and tornadoes can separately put individuals into direct interaction with microorganisms, increasing the risk of infected injuries and sepsis. As previously reported tornadoes in Joplin, Missouri caused many cases of mucormycosis by *Apophysomyces trapeziformis* due to contamination of wounds.[20]

Furthermore, the development of microorganisms in response to stressors such as heat waves and droughts as well as chemical or toxic waste enables microorganisms to endure ecological change and evade the mammalian immune system.[4]

2.1.A. Flooding disasters

Following rainstorms, tropical cyclones, and tsunamis, flooding occurs, result in the overflow of water from rivers and oceans which enters homes, businesses, and roadways leading to their damage.[9] Also flooding causes disruption of soil and brings soil microorganisms into direct interaction with humans leading to respiratory and gastrointestinal infections.[21]

The development of toxin-producing molds inside homes occurred following flooding and water damage in several New Orleans households after Hurricane Katrina of 2005 which led to respiratory diseases.[22] After Hurricane María of 2017, water-damaged households in Puerto Rico showed the growth of filamentous fungi, including *Aspergillus spp.*[23]

Molds rising within humid or water-damaged households is occasionally accompanied by a higher risk of asthma in kids and grownups. Humans getting ill due to increased exposure to fungal toxins is a phenomenon known as “sick building syndrome”.[24] After the 2004 Indian Ocean tsunami and the 2011 Japanese tsunami, many fungal infections were reported such as *Fusarium spp*., *Mucor spp*., *Aspergillus fumigatus*, and *Scedosporium apiospermum.*[25]

Legionellosis (a serious type of pneumonia) occurred in big numbers after the earthquake and tsunami in Japan of 2011 because of inhaling droplets of soil-contaminated water that carried *Legionella spp*. as well as *Aspergillus fumigatus.*[9] Overflow of wastewater and sewage due to floods exposes contaminated waters with human waste, which can lead to waterborne infections such as typhoid.[26]

Various disease vectors such as mosquitoes bloom after floods in tropical regions, like *Anopheles spp*. mosquitoes harboring malaria or *Aedes spp*. mosquitoes causing yellow fever and dengue as well as Zika virus. Mosquito-borne illnesses are responsible for more than 700,000 deaths worldwide per year.[19]

2.1.B. Dust-related disasters

Tornadoes, earthquakes, dust storms, and droughts increase the rates of bacterial and fungal pneumonia. In 1977, a windstorm in California resulted in an outbreak of the soil fungus *Coccidioides immitis*. Like earthquakes and dust storms, drought is a main cause of coccidioidomycosis spread in areas with dry soil, forming dust.[27]

2.1.C. Wildfires

Wildfires are accompanied by an elevated risk of respiratory infections. Moreover, wildfires alter the bacterial and fungal structure of the soil. This led to the selection of microorganisms that possess stress-resistant spores and a high degree of heat tolerance increasing the risk of microbial infection at normal body temperature. Viable fungi and bacteria are transported via the smoke from fires, with concentration in the smoke far more than the normal air. “Pyroaerobiology” is a term used to describe how microorganisms act in case of fire and smoke.[28]

2.1.D. Heat Extremes

Heat waves as well as extreme heat events are considered stressful events for most creatures. Urban areas are more liable to heat, due to the “heat island” phenomenon that resulted from reduced green spaces as well as airflow and excess building materials. Excess exposure to heat has forced microbes to adapt to heat, resulting in human infections with pathogens that were not able to survive human body temperature in the past as environmental fungi which used to grow best below 37°C.[9]

Weakens of the immune system caused by the human immunodeficiency virus (HIV) and by the excess use of immunosuppressive drugs together with the adaptation of fungi to higher temperatures resulted in the rise of fungal pathogens in the 20th century. *Candida auris* developed temperature tolerance and changed from a firmly ecological organism to a pathogenic one.[29]

2.2. Man-made Disasters

Earthquake-mediated infections are increased by human activities such as oil exploration and production.[30] Contamination of water supplies due to failed wastewater treatment plants resulted in outbreaks of the gastrointestinal parasite Cryptosporidium.[9] Melanotic and radiophilic fungi colonized the damaged nuclear power plant reactor of Chernobyl (Ukraine, 1986) and thus gained the ability to develop in extreme circumstances.[31] Furthermore, microorganisms showed the ability to grow in acidic and heavy-metal media which occur in contaminated mining wastewater.[32]

The danger in these stress adaptations to those human-caused conditions is that these microbes can cause human infections. For example, the antioxidant response to ionizing radiation could help a microorganism to overcome immune-mediated oxidative bursts[33]. Also, the capacity to endure acidic environments could enable persistence within the host phagolysosome and escape from destruction.[34] Furthermore, the growth of a spore-coat or thickened cell wall will lead to overcoming of stresses such as antimicrobial peptides, antibiotics, and oxidative degradation.[9]

Impacts of Climate Change on Zoonoses

According to the World Health Organization, zoonoses are known as diseases and infections communicated among vertebrate animals and humans. Infected vertebrate host affect humans by zoonoses through direct or indirect interaction by mechanical or biological vectors. Some zoonotic diseases need more than one vertebrate host or invertebrate to complete their infectious cycle.[7] Reports have identified the connections between the rise of different zoonoses and climatic change and hazards.[7,35]

1. Vector-borne zoonoses.

Infected arthropods like mosquitoes, ticks, flies, and blackflies convey vector-borne diseases. Temperature has a direct impact on vector endurance and rates of reproduction, affecting their spreading, abundance, habitat suitability, intensity and activity, and rates of growth, survival, and multiplication of microorganisms in vectors.[7]

Heavy rainfall creates suitable reproduction areas for vectors such as mosquitoes. Furthermore, heavy plantations developing after rainfall create shelter and accommodation for vectors.[36] On the other hand, climate change can lower the abundance of vector species. For example, a report from Kenya showed a decrease in *Aedes aegypti* pupae after a heat wave during 2013-2019 in the town of Chulaimbo, in Western Kenya.[37]

1.1. Mosquito-borne zoonotic diseases

Mosquitoes harbor many microorganisms, such as viruses, parasites, and bacteria. These microorganisms are accountable for the augmentation and conveyance of many zoonotic diseases like Zika, dengue, and chikungunya viruses. Mosquito multiplication and activity together with rates of blood meals, and more rapid digestion are enhanced by elevated temperatures. Furthermore, high water temperature help mosquito larvae to grow fast and thus improve the transmission of various pathogens [38].

1.1 A. Malaria

Anopheles mosquitoes transmit five genera of Plasmodium parasite namely *Plasmodium falciparum*, *P. vivax*, *P. ovale*, *P. malariae* and *P. knowlesi* which are responsible for malaria infection which causes fever, shaking chills, aches, and headaches. In 2017, 219 million cases and 435,000 deaths due to malaria were reported. Malaria is one of the top 10 causes of morbidity and mortality within sub-Saharan Africa.[39] Tropical regions with high temperatures, excess rainfall, elevated humidity, and reduced altitudes are optimum for mosquito multiplication and survival.[36] Studies mentioned that the malaria burden will be more at high altitudes as the temperature rises.[36 39,40]

1.1.B. Dengue

Dengue is caused by Flavivirus and transmitted by mosquitoes. It is widely distributed in tropical and subtropical areas. It causes fever, rash, nausea, vomiting, aches, and pains in joints, bones, and eyes. Endemic countries show an increase in the rates of dengue. It was reported that dengue is the fastest arbovirus to spread in the world threatening a half-billion human beings worldwide with extremely high rates of infection in the urban and peri-urban areas of the American continent. [40,41] Dengue is an exclusively vector-borne disease that is expected to rise by 26% worldwide.[41]

1.1.C. Chikungunya

Chikungunya indicates the “illness that bends up the joints”, it is a viral disease transmitted by mosquitoes via an alphavirus from the *Togaviridae* family causing fever and joint pain. Chikungunya has evolved rapidly, and reemergence of the chikungunya virus is a worrying public health problem because the virus caused many epidemics in Africa, Asia (India), Europe (Italy), and the United States of America (USA).[40]

1.1.D. Japanese Encephalitis

One of the main reasons of viral meningoencephalitis is Japanese encephalitis (JE), due to a Flavivirus. JE is prevalent in various countries worldwide mainly spreading from Japan to India and Pakistan in Asia. *Culex* mosquitoes are responsible for conveying JE between animals. Natural transmission is kept amongst wild and domestic birds and pigs. The ongoing agricultural applications, such as expanding irrigation favor vector propagation, and raising farm animals that act as reservoir hosts lead to increased transmission to humans. Safe and effective JE vaccines are available, yet JE is a major public health concern in endemic areas.[42]

1.1.E. Rift Valley Fever

Rift Valley fever (RVF) is a severe viral hemorrhagic fever illness developed due to the *Phlebovirus* genus of the *Bunyaviridae* family. It infects domestic animals and individuals extensively in Africa and the Arabian Peninsula in Asia. The disease is transmitted by mosquito bites, mostly *Aedes spp.* and *Culex spp*. Direct or indirect interaction with blood or tissue of diseased animals can transmit the disease.[43] It was reported that RVF is considered a huge threat to the health of individuals and animals thus affecting the economy and food security.[43]

1.1. F. West Nile Fever

West Nile viral (WNV) disease is due to the West Nile virus of the genera *Flavivirus*. It is spread by the *Culex* mosquito. WNV is transmitted by many mosquito vectors and hosts such as birds and horses as well as other mammals which cause a lot of human illnesses. The clinical picture of most human illnesses is mild febrile disease and asymptomatic. Aggressive forms such as encephalitis, meningoencephalitis, or meningitis may occur. Recently, WNV was considered among the most significant zoonotic illnesses of alarm to USA residents. It was reported as recurrent epidemics in Africa, Europe, Asia, Australia, and the Middle East.[44]

1.1. G. Yellow Fever

Yellow fever disease occurs due to the yellow fever virus belonging to the genus Flavivirus. It is spread by the bite of infected *Aedes* mosquito species. Yellow fever is a viral hemorrhagic fever and one of the utmost dangerous diseases in history. Yellow fever epidemics are always established in South America and Africa, distressing the urban and rural inhabitants. Reports indicated that there was a rise in epidemics of yellow fever in urban areas of some African countries like Angola and the Democratic Republic of Congo.[40] New cases were discovered in Kenya and China. In 2013, the World Health Organization reported that 47 countries in Africa and Latin America were considered as endemic for yellow fever with an expected annual burden of 200,000 cases and 60,000 deaths.[40] Nowadays, vaccines are available for yellow fever.[45]

1.1. H. Zika Fever

Zika virus is a member of flaviviruses. It is caused by a mosquito-borne disease often known as Zika fever, symptoms include fever, rash, headache, joint pain, red eyes, and muscle pain. Zika virus infection is responsible for birth defects and is related to Guillain-Barré syndrome. In 2015, reports indicated that the Zika virus was responsible for severe epidemics in the American regions, which showed the spread of the disease outside Africa and Asia. In the same year, an epidemic of Zika virus hit Brazil and then South and Central America.[46,47] So far, there is no approved vaccine for Zika fever.[46]

1.2. Sand fly-borne zoonoses.

Sand flies transmit leishmania, a protozoan parasite causing the leishmaniasis_disease. The biting rates of sand flies increase with higher temperatures and the protozoa inside the vector flourish. In Europe, sand flies are spread in the south and transmit leishmania, due to *Leishmania infantum* causing fever, weight loss, swelling of the spleen and liver, and anemia, thrombocytopenia, leucopenia, neutropenia, pancytopenia. Warmer temperatures in northern Europe are anticipated and rainfall will upsurge. These climate variations are expected to widen the array of sand flies to northwestern and central Europe.[48]

1.3. Tick-borne zoonoses

The elevated temperature affects ticks egg production, population density, development cycle, and spread of ticks due to alterations of host species like deer, rodents, and birds. *Ixodes scapularis* is the main tick vector causing Lyme disease in North America, due to *Borrelia burgdorferi,* a pathogenic spirochete, responsible for conveying Lyme disease to people during blood-feeding. Symptoms of Lyme disease include fever, headache, fatigue, and a characteristic skin rash known as erythema migrans. Cases reach 85,000 annually in Europe from April through October. The rate of Lyme borreliosis has amplified in numerous European countries. The rise in winter temperatures may widen the spread of Lyme borreliosis into higher altitudes.[49]

1.4. Other vector-borne diseases

Other vector-borne zoonotic diseases include onchocerciasis or river blindness transmitted by blackflies, Scrub typhus transmitted by mites, Chagas disease transmitted by triatomine bugs, and African trypanosomiasis transmitted by tsetse flies. Several reports confirmed the link between the illnesses spread by these vectors and climate change like temperature, extent of sunshine and rainfall, as well as humidity.[7,35]

2. Waterborne zoonoses

Contamination of water with water-borne pathogens occurs due to excess precipitations, flooding, and extreme events such as tornados and hurricanes. Drinking, food processing, and use of contaminated water for recreational purposes cause transmission of infections to humans. Infectious waterborne zoonosis includes Campylobacter and E. coli (O157: H7 serotype) as well as Cryptosporidium, Leptospira, and Vibrio species as reported in the 2022 Pakistan floods50. In 2022, a rise of hepatitis A took place in the United States 50,51. Schistosomiasis infection hazard in East Africa is expected to rise by 20% over the next 20-50 years because of climate variation and building dams 7.

3. Foodborne zoonoses

Ingestion of food contaminated with microorganisms or toxins leads to foodborne illness. Climatic hazards such as elevated temperatures can augment multiplication cycles and the development, endurance, and spread of foodborne pathogens. The risk of campylobacter infections, due to bacteria that can cause diarrhea, in the European Union was related to weekly average temperatures. For every degree rise in weekly temperature in the European Union member countries there is an increase in salmonellosis infection. Food and waterborne norovirus outbreaks due to climatic hazards such as excess rainfall and floods, leading to contamination of fresh and marine water sources have been reported 1,7.

4. Rodent-borne zoonoses

Plague and hantavirus infection are major rodent-borne zoonoses. Climatic change has a great influence on rodent populations. Warm wet winters and springs led to widespread rodent populations. Furthermore, human-rodent interactions increased because rodents escape indoors in search of water and food in cases of heat waves. Also, excess rainfall yields excess crops and foods, helping rodents to breed more often and enlarge the population. Fleas feeding on rodents transmit plague which is due to the bacterium Yersinia pestis. The El Niño-Southern Oscillation-induced climate variances, temperature, and rainfall alterations are related to plague rise in the USA. It has been predictable that every 1 ◦C degree rise in spring temperatures would lead to a >50% rise in Y. pestis incidence in its reservoir host 52.

Hantaviruses are conveyed to people through inhalation of virus aerosol from infested rodents’ excreta. Amplified plants after excess rainfall have been related to the rise in the deer mouse population. El Niño-related weather events were responsible for the increase in hantavirus infection in the USA and Latin America 53.

Another rodent-borne emerging pathogen is the Monkeypox, an infectious viral disease. It begins with symptoms such as fever, chills, headache, muscle aches, backache, and fatigue. In 2002, it became a global threat 54.

5. Airborne zoonoses

Bovine tuberculosis is caused by Mycobacterium bovis, which is transmitted from animals to individuals through inhalation of aerosols. Numerous studies showed that the United Kingdom and Ireland are subjected to higher chances of excessive rainfall events and drier hotter summers that affects the survival of Mycobacterium bovis, thus the hazard of bovine tuberculosis in the British and Irish setting is elevated 55–57.

Highly pathogenic avian influenza due to the H5N1 virus is also a zoonotic illness, spreading from infected birds through droplet/aerosol transmission. Studies showed that some of foodborne microorganisms like Salmonella and E. coli O157: H7 as well as Staphylococcus aureus (Methicillin-resistant) can also be transmitted through airborne routes in farm and rural areas and animal processing settings35. Other reports showed that soil-borne microorganisms like Hantavirus as well as anthrax (B. anthracis), and Q fever can also be transmitted through airborne routes. Strong wind can spread airborne microorganisms from endemic areas to other far regions 7,35.

Impacts of Climate Change on Antibiotic Resistance

Effective antibiotics against bacterial infections are of utmost importance for maintaining healthcare systems. Another challenge facing humanity because of climate change is the rise of antibiotic-resistant organisms.[6]

1. Elevated temperature and antibiotic-resistance

Elevated temperature is related to increased bacterial proliferation and infections and the acquisition of antibiotic-resistance genes by horizontal gene transfer. As climate change worsens the association of high numbers of infections and the rise of antibiotic-resistant microorganisms will cause the rise of antibiotic-resistant bacterial strains.[58]

Human mental health is affected by higher temperatures. As proper decision making is affected, including health workers prescribing antibiotics which may lead to excess use of antibiotics.[52] Unnecessary antibiotic prescriptions have also increased with the rise of telemedicine because of the COVID-19 pandemic raising the risk for more antibiotic resistance.[60]

Higher temperatures and extreme weather events together with the rise of infections affect human health leading to more hospitalization with subsequent exposure to antibiotic-resistant bacterial strains.[61]

2. Floods and antibiotic resistance

Floods lead to increased risk of infections, population migration, and overcrowding. Eutrophication, including the accumulation of nitrogen fertilizers running off from soil to water sources by flooding increases antibiotic resistance.[6] Sewage as a known reservoir for antibiotic-resistant genes can contaminate water sources due to the destruction of sanitation infrastructures by floods leading to the spread of antibiotic-resistant bacterial strains.[62]

Flooding can also spread industrial pollutants such as heavy metals into the environment, increasing antibiotic resistance. This is because heavy metal ions are known to co-regulate genes responsible for antibiotic resistance leading to reduced antibiotic susceptibility.[63] Another cause of gene exchange in bacteria in water sources is microplastics, which also promote the formation of biofilms in bacteria increasing antibiotic resistance. An elevated temperature favoring the flourishing of *Vibrio* species together with flooding spreading microplastics can lead to the emergence of *Vibrio*-resistant strains.[64]

3. Drought and antibiotic resistance

During droughts, water is scarce leading to reduced available clean water sources and crowds sharing the same source of water leading to outbreaks of infections.[6] Since water is scarce crops are affected and malnutrition rises increasing the hazard of acquiring antibiotic-resistant microorganisms in malnourished children due to reduced immunity which increases liability to severe infections. A study showed the increased spread of antibiotic-resistant strains of *Mycobacterium tuberculosis* due to reduced humidity aided by increased population densities and malnutrition.[58]

Impacts of Climate Change on Human Immunity

Climate change has various effects on human health and immunity from direct injuries during disasters to indirect effects such as cardiovascular strokes due to excess heat and respiratory diseases due to lung injuries affected by wildfires and pollutants such as particulate matter ($PM_{2.5}$).[16]

1. Nutrition

The human ability to deal with microorganisms has been affected by climate hazards by reducing body immunity.[65] Body malnutrition can affect immunocompetence to disease. This is a result of climatic disturbance of land and marine food supply and the decreased concentration of useful nutrients in crops due to pollution by CO2. Thus, increasing the risk of outbreaks by *Cryptosporidium*, measles, and cholera.[4]

Vitamin D deficiency occurs at elevated levels of greenhouse gases and aerosols which absorb ultraviolet radiation reducing the cutaneous synthesis of vitamin D, thus increasing the susceptibility to viral infections.[66,67] This explains how the initial COVID-19 outbreak occurred in Lombardy, Italy where the population is known to suffer from vitamin D deficiency.[67]

2. Gut Microbiome

Climate change alters the gut microbiome's composition, which lowers immunity.[16,,65] The human gut microbiome is formed of 1,000 species of bacteria and 100 trillion microorganisms that are responsible for vitamin production, food metabolism, and the regulation of immune mechanisms against microorganisms.[68] It was reported that the occurrence of *Bacteroides species* in the intestine is responsible for the production of T helper 17 cells **(**Th17) CD4+ pro-inflammatory T cells, which are involved in combating some infections.[69]

The capacity of the host to generate regulatory T-cells is related to the nature of the diet, particularly its fiber and fat structure. It was reported that climate change has its effects on nutrition, and soil microbiota which later altered the microbiome's nature in several societies.[61,65]

3. Diseases and Infections

Studies showed the link between the prevalence of diabetes and elevated temperatures associated with dehydration and thermal stress leading to changes in insulin absorption and diffusion. These diabetic individuals may have a lot of immunological problems making them more susceptible to infections.[65, 71]

Outbreaks of influenza were attributed to the failure of the human immune system to cope with great temperature variations [16,65]. Also, stress due to extreme weather events causes alterations in cortisol levels and down-regulation of inflammatory response, which reduces the body’s immunity.[16,65]

Discussion

Global issues like climate change transcend national boundaries. Hence, comprehensive research is compulsory to determine the direct and indirect links between climatic variation and dangers that are caused by biological processes, the natural environment, and other human activities. This will facilitate the application of an action plan for protection and prevention against all anticipated hazards as well as a better knowledge of the dangers posed by climate variation.[72]

In 2015, the UN stated that dealing with climate change requires massive international organization and collaboration. At that time, the

UN approved several climate-related agreements -including the Paris Agreement on Climate Change, the Sustainable Development Goals of Agenda 2030, and the Sendai Framework for Disaster Risk Reduction 2015–2030.[73] Following these agreements, other global institutions and partners are addressing climate change issues and mitigating disaster risks for sustainable development, for example by releasing annual reports on the status of climate services. This information provides insight into how to facilitate the creation and implementation of strategies for adaptation requirements for initial warning systems.[74]

Accepting this fact, adjusting to the changing climate, and doing everything in our power to protect people, animals, and our shared environments from its negative effects is of the utmost importance. One of the best solutions to this issue is the One Health concept, which aims to optimize and sustainably balance the health of ecosystems, animals, and people. [63]

A One Health High-Level Expert Panel was established by four international organizations, the Food and Agriculture Organization, the World Organization for Animal Health, the United Nations Environment Program, and the World Health Organization to collect, distribute, and disseminate consistent scientific data regarding the relationships between environmental, animal, and human health. [75] Data on extreme weather forecasting and an understanding of the earth system can be obtained by using modern technologies such as digital earth tools. Improved digital systems to track energy consumption and greenhouse gas emissions are crucial for managing climate change. [77]

Investments from various entities (e.g., governmental segments, non-governmental organizations, corporations, agencies such as the World Bank, etc.) are required to foster research and innovation in the necessary sectors to comprehend the relationships between humans, animals, and the environment. Both national and international efforts are needed to manage the dangers associated with climate change and improve early detection, early identification, early warning, and rapid response. [72] "Open Science," or making research accessible to everybody, and international cooperation is essential for promoting knowledge of the impacts of climate fluctuation and improved health governance. To make science serve society and close gaps in research, technology, and innovation both inside and between nations, the "Open Science" concept is crucial. [72]

It is critical to gain insight into the habitats of microorganisms (plant, animal, and human) and how they can infect humans to promote early identification, prediction, and control of emergent epidemics. [75] Due to the outdated and rigid public health system, the poor collaboration within sectors because of insufficient data collection, and the little budget available, putting the recommendations into practice is challenging. [76]

Despite all these difficulties, governments throughout the world are currently considering the effects of climate change as their top priority. The keen participation of almost 200 nations in the Conference of the Parties (COP)-26 agreements in Glasgow, United Kingdom, last year, was indicative of this. To solve the climate change issue, there must be strong support from the public, enterprises, scientific groups, and governments.[79]

Conclusion

Climate change and global warming are the greatest hazards to humanity in the twenty-first century. Extreme weather events, such as heat waves, droughts, floods, dust storms, typhoons, hurricanes, and wildfires, are examples of short-term risks that can be caused by climate change. These events can also impact the frequency or distribution of these natural disasters. The effects of climate change on emerging pathogens and human immunity are numerous. Antibiotic resistance and human/pathogen exposure, notably zoonoses, are both extrapolated by climatic change. Therefore, to ascertain the connections between climate variation and hazards resulting from biological processes, the environment, and other human activities, extensive research is required. This will enable an improved understanding of the risks posed by climate fluctuation as well as the implementation of an action plan for protection and mitigation against all predicted hazards.

Author Contributions

AE; main concept, idea and writing manuscript. NY; collection of data and information. FA; revising and editing data and manuscript. MEE; revising and editing data and manuscript. ME; writing and revising the manuscript.

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