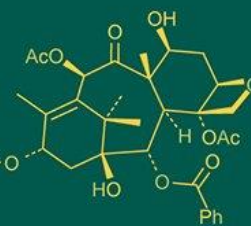
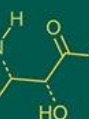
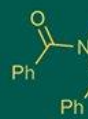


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Anthropogenic drivers of bacterial and viral shifts in wildlife

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Abstract

Rapid population expansion and industrial development have intensified the demand for increased food production and resource supply. This pressure has resulted in the encroachment of human populations into forested regions, increasing interactions with wildlife, their parasites, and disease vectors. Activities such as wildlife trade and consumption, water contamination, and improper waste disposal have become more common. At the same time, agricultural and livestock production has expanded rapidly, often without proper planning, contributing to deforestation and disrupting ecosystems that are crucial for maintaining global climatic and ecological stability. Human impact is not limited to terrestrial environments; marine ecosystems are also severely affected. Pollution and overexploitation of aquatic resources have reduced fish stocks and other marine life, forcing coastal communities to migrate inland. These combined factors place additional strain on infrastructure, increasing the need for housing, sanitation, and healthcare services. Consequently, many populations become vulnerable, particularly in the face of climate change and the growing risk of emerging and re-emerging infectious diseases. This article examines how human-driven factors—including climate change, urban expansion, deforestation, wildlife trade and consumption, and unsustainable agricultural practices—contribute to the emergence and re-emergence of zoonotic diseases. These include viral pathogens such as Ebola, hantaviruses, Hendra virus, Nipah virus, rabies, and SARS-CoV-2; bacterial infections like leptospirosis, Lyme disease, and tuberculosis; as well as parasitic and fungal diseases. Together, these threats represent a significant global health concern. The discussion also highlights the urgent need to adopt the One Health approach, emphasizing interdisciplinary collaboration to improve public awareness, enhance education, and strengthen efforts to prevent and control zoonotic diseases for the benefit of both humans and animals.

Keywords: Zoonoses, climatic changes, anthropic actions, emerging diseases, Hendra virus, rabies, hantavirus, leptospirosis, COVID-19, tuberculosis

1. Introduction

Zoonotic diseases originate from domestic or wild animals and therefore require close cooperation between animal health and public health authorities. The term “emerging zoonosis,” as defined by the World Health Organization (WHO), the Food and Agriculture Organization (FAO), and the World Organisation for Animal Health (WOAH), refers to a newly identified or evolving pathogen, or one that existed previously but is now increasing in incidence or spreading to new geographic regions, hosts, or vectors. The emergence of zoonotic diseases is driven by multiple interconnected factors. These include: (i) human-related activities such as urbanization, agricultural expansion, deforestation, globalization, socio-economic changes, the use of agrochemicals, antimicrobial misuse, and behaviors like bushmeat consumption, livestock production and trade, and increased human-animal interaction; (ii) environmental influences such as changes in temperature, drought, and wind patterns; and (iii) biological processes including genetic mutations, drift, and reassortment. Together, these drivers contribute directly or indirectly to the emergence and re-emergence of pathogens such as Ebola virus, Hendra virus, Middle East Respiratory Syndrome coronavirus (MERS-CoV), Nipah virus (NiV), and the recently identified SARS-CoV-2. This review focuses on the key human-driven activities linked to the rise and reappearance of zoonotic diseases.

2. Anthropogenic Actions

A summary of the potential effects of anthropogenic activities—such as climate change, urbanization, deforestation, wildlife trafficking and consumption, and unsustainable agricultural intensification—as key drivers of the emergence and re-emergence of pathogens.

2.1. Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC), climate change refers to statistically significant variations in average climatic conditions, including natural variability^[11, 12]. The United Nations Framework Convention on Climate Change defines it as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”^[13].

Although global warming can occur due to natural processes, human activities have significantly accelerated this phenomenon in recent decades. Anthropogenic pressures such as urbanization, deforestation, and agricultural expansion contribute to biodiversity loss across terrestrial, aquatic, and marine ecosystems, as well as to the degradation of ecosystem services^[14].

The current climate crisis is advancing more rapidly than previously anticipated^[15]. Over the past 50 years, the ecological footprint of human activity has increased by nearly 190%, reflecting a growing imbalance between humans and the environment, alongside profound environmental and societal transformations^[16]. Climate change poses serious risks to human populations, including the potential for large-scale migration toward more favorable environments, particularly from coastal regions to inland areas.

Global sea levels have risen between 16 and 21 cm since 1900 and continue to increase at a rate exceeding 3 mm per year in recent decades^[14]. Deforestation is one of the major contributors to climate change and has a direct impact on disease dynamics. The destruction of natural habitats increases interactions between humans and wildlife, either through direct human activity or through wildlife adaptation to human-altered environments^[17].

Temperature changes also play a critical role in disease ecology. Many pathogens and their vectors lack internal temperature regulation mechanisms^[18, 19], making them highly sensitive to environmental temperature variations. As a result, changes in temperature can alter their geographic distribution^[20]. Furthermore, the presence of hemolytic bacteria in Arctic environments highlights the risks associated with ice melting, which may release previously trapped microorganisms and increase their contact with humans and animals. This process is linked to rising global temperatures and leads to habitat disruption, ecosystem transitions, and recolonization^[21].

2.2. Deforestation

One of the primary factors contributing to the emergence of new diseases is population growth^[22]. It is projected that the global population will reach approximately 10 billion by 2050. As urban areas become increasingly crowded, populations expand into previously undisturbed natural habitats, including forests. At the same time, rising food demand drives the conversion of natural ecosystems into agricultural land. According to^[23], three interconnected

global trends—income growth, urbanization, and globalization—are intensifying the risk of zoonotic disease emergence. Deforestation leads to biodiversity loss and ecological imbalance, which can facilitate the spread of infectious diseases^[24].

Large-scale deforestation, such as that occurring in the Amazon, plays a significant role in environmental degradation^[25]. Data indicate that deforestation rates have continued to rise in recent years. For instance, during the first eight months of 2021, deforestation increased by 8.2% compared to the same period in the previous year. Additionally, preliminary data suggest that extensive areas of forest were lost in 2022^[26]. This trend is particularly concerning, as studies suggest that the loss of 1 km² of Amazon forest may be associated with an increase of up to 27 malaria cases^[27].

Changes in rainfall patterns due to deforestation are expected to contribute to outbreaks of vector-borne and waterborne diseases^[28]. The Amazon rainforest, which experiences approximately 11,000 km² of deforestation annually, plays a crucial role in regulating regional climate and water vapor transport across South America^[29]. Deforestation is commonly driven by the expansion of agriculture, livestock production, and mining activities. These activities increase human exposure to wildlife and their associated pathogens^[30, 31]. In regions such as the Amazon, the interaction between environmental degradation, climate change, changes in vector dynamics, human migration, pathogen evolution, and socioeconomic challenges creates conditions conducive to the emergence and re-emergence of infectious diseases^[32]. Diseases such as rabies have been linked to deforestation and increased human encroachment into wildlife habitats. For example, outbreaks in the Amazon Basin have resulted in significant mortality^[33].

Brazil is one of the world's leading agricultural producers, with continued growth in grain production, particularly soybeans and corn^[34]. However, land-use data indicate that a substantial proportion of deforested land is converted into pasture for cattle ranching^[35]. Similarly, the Brazilian Cerrado biome has experienced extensive environmental degradation, with a significant portion of its area converted for agricultural use^[36]. While deforestation is often intended to enhance food production, it can negatively impact climate stability, which is essential for sustainable agricultural productivity. Research suggests that future climate changes may significantly reduce the availability of suitable land for rainfed agriculture^[37].

Therefore, the implementation of effective global policies to protect forests is essential. Forest ecosystems play a critical role in maintaining climate stability, preserving biodiversity, and regulating interactions between pathogens and their natural hosts. Protecting these ecosystems is crucial for reducing the risk of emerging and re-emerging infectious diseases.

2.3. Trafficking and Consumption of Wild Animals

Food security plays a critical role in preventing the emergence and re-emergence of diseases and in safeguarding human health. The COVID-19 pandemic has significantly affected food systems, animal health, and human well-being^[38-40]. Additionally, the increase in poverty levels during the pandemic has intensified food insecurity, which in some cases drives populations toward

the consumption of wild animals ^[41]. Although recent data on wildlife consumption are limited, it is well established that wild animals form part of the diet in many regions worldwide. According to the FAO report “*The State of the World’s Biodiversity for Food and Agriculture*”, more than 53.5% of households in certain communities across Asia, Africa, and Latin America relied on wild animals and plants between 2004 and 2010 ^[42].

Research conducted in Rio Branco, Acre (Brazil), involving 550 participants, revealed that 78% had consumed or currently consume meat from wild animals ^[43]. Other studies also highlight the wide diversity of wildlife species used as food sources ^[44, 45]. In many remote or isolated areas, such as rural villages, hunting remains a primary means of subsistence ^[46]. In the Amazon region, for instance, bushmeat constitutes an essential component of the diet in several communities ^[47]. China is recognized as one of the largest consumers of wildlife, both for dietary purposes and traditional medicine ^[48]. While the exact origin of SARS-CoV-2 remains uncertain, early cases were associated with the Huanan South China Seafood Market ^[49]. Live animal markets, often referred to as wet markets, create environments where humans and multiple animal species are in close proximity, facilitating pathogen transmission. These markets are also vital for food distribution in many countries ^[50].

Such environments have been linked to the emergence of various epidemic and pandemic diseases, including COVID-19 and multiple subtypes of influenza A viruses. They also serve as potential sources of foodborne pathogens. Wild animals can harbor numerous known infectious agents, including those responsible for tuberculosis ^[51], leptospirosis ^[52], rabies ^[53], and brucellosis ^[54], as well as unknown or emerging pathogens. Another growing concern associated with wildlife consumption is antimicrobial resistance (AMR). For example, Extended-spectrum β -lactamase and AmpC (ESBL/AmpC)-producing *Escherichia coli* have been identified in wild boars, emphasizing the importance of this issue within the One Health framework ^[55]. Strengthening food safety inspection systems and surveillance is essential to protect both human and animal health. Equally important is the promotion of public awareness through policies focused on food safety, environmental protection, and social education.

Wildlife trafficking is another critical issue that requires greater attention. This illegal trade is estimated to generate between USD 7-23 billion annually, making it the fourth most profitable form of trafficking globally, after drugs, human trafficking, and weapons ^[56]. Beyond contributing to biodiversity loss and species extinction, wildlife trafficking disrupts ecosystems and increases the likelihood of pathogen transmission to humans.

Illegal wildlife trade networks often supply animals for consumption in various markets ^[48]. This highlights the need for stronger regulatory measures and enforcement by public authorities. In response to the COVID-19 pandemic, China implemented a ban on the trade and consumption of wild terrestrial animals, aiming not only to protect public health but also to curb illegal trade and conserve endangered species ^[57]. However, current wildlife trade regulations remain insufficient, partly due to the perception of wildlife as a resource to be exploited. Increasing public awareness

and education about the risks associated with wildlife consumption and the importance of conservation are essential steps toward reducing these practices ^[58].

3. Human-Host-Environment Interaction

The relationship between hosts, their microbiomes, pathogens, and the environment forms a complex four-way interaction that plays a crucial role in disease emergence and epidemic risk prediction (Figure 2) ^[59]. Human-driven environmental changes significantly increase contact between wildlife and human populations, thereby facilitating the transmission and introduction of pathogens ^[60-66]. These interactions are largely driven by alterations in ecosystems caused by anthropogenic activities.

The impacts of these changes extend beyond infectious diseases. Environmental pollutants associated with human activity have been linked to chronic conditions such as Parkinson’s disease and diabetes ^[67-70]. Additionally, there is evidence suggesting that exposure to certain herbicides, such as glyphosate (N-phosphonomethylglycine), may contribute to bacterial cross-resistance, including the development of ESBL-producing Enterobacteriaceae ^[71]. The misuse and overuse of antibiotics remain major contributors to antimicrobial resistance (AMR) ^[72-74]. Notably, increasing cases of carbapenem resistance have been reported, posing a serious public health concern, particularly in regions such as Africa where access to these antibiotics is limited ^[75].

Overall, environmental changes driven by human activities enhance interactions among pathogens, vectors, wild and domestic animals, and humans ^[76]. These dynamics can disrupt ecological balance, including the loss of species that act as natural reservoirs for pathogens. As a result, pathogens may spill over into new hosts, including humans, increasing the risk of disease emergence.

4. Selected Emerging and Re-Emerging Viral Pathogens

4.1. Ebola Virus

The Ebola virus belongs to the *Filoviridae* family and is characterized as an enveloped, single-stranded, negative-sense RNA virus with a genome of approximately 19 kb ^[77]. The *Filoviridae* family comprises three genera: *Ebolavirus*, *Marburgvirus*, and *Cuevavirus*. Within the *Ebolavirus* genus, five species have been identified: Zaire ebolavirus, Sudan ebolavirus, Taï Forest ebolavirus, Bundibugyo ebolavirus, and Reston ebolavirus, corresponding to EBOV, Sudan virus (SUDV), Taï Forest virus, Bundibugyo virus (BDBV), and Reston virus, respectively ^[78]. In the past decade, EBOV, SUDV, and BDBV have been responsible for repeated outbreaks of Ebola virus disease (EVD) in Central and West Africa, with case fatality rates ranging from 30% to 90% ^[79]. More recently, Bombali virus (BOMV), a newly identified ebolavirus species, has been detected in bats in Sierra Leone and Kenya ^[80, 81]. Similarly, Mengla virus (MLAV) has been identified in fruit bats in China.

Research indicates a strong association between anthropogenic activities and the emergence of EVD. Forest degradation and fragmentation, in particular, have been linked to increased outbreak frequency. Deforestation can alter the distribution, behavior, and abundance of reservoir species, thereby increasing the likelihood of contact between infected animals and humans ^[82].

4.2. Hantaviruses

Hantaviruses are members of the Bunyaviridae family and are single-stranded, negative-sense RNA viruses. They are responsible for two major human diseases: hemorrhagic fever with renal syndrome (HFRS) and hantavirus cardiopulmonary syndrome (HCPS). To date, 28 hantavirus species have been identified. Their primary reservoirs include rodents, insectivores, and bats, and transmission to humans generally occurs through inhalation of aerosolized excreta from infected rodents [83]. The risk of infection is closely linked to human-rodent interactions. In developed countries, certain occupational groups—such as forestry workers, laboratory personnel, hunters, and pet rodent owners—are at higher risk [84-87]. In contrast, in rural and developing regions, exposure risk is more widespread among the general population [88, 89].

Serological studies conducted globally show varying prevalence rates, ranging from 6% to 36% [90-95]. Due to their transmission dynamics and adaptability, hantaviruses are considered potential candidates for future pandemics [96]. Environmental and landscape-related factors—including climate, land use, vegetation, soil characteristics, and human population distribution—have been identified as key determinants of hantavirus risk, all of which are influenced by anthropogenic activities [97].

4.3. Hendravirus

Hendra virus is closely related to the *Henipavirus* genus and shares approximately 78% sequence similarity in the nucleocapsid (N) gene with Nipah virus (NiV) [98]. First identified in Australia in 1995, Hendra virus primarily causes severe disease in horses and has also been shown to infect animals such as cats and guinea pigs under experimental conditions [99]. In humans, infection can lead to severe encephalitis accompanied by respiratory symptoms. The natural reservoir of Hendra virus is fruit bats of the genus *Pteropus*, which are widely distributed across South and Southeast Asia, northern and eastern Australia, Madagascar, and parts of the Pacific region. The expansion of human populations into wildlife habitats is considered a major factor driving the emergence of Hendra virus infections [64].

4.4. Nipah Virus

Nipah virus (NiV), a member of the *Paramyxoviridae* family and *Henipavirus* genus, is an enveloped virus with a non-segmented, negative-sense single-stranded RNA genome [100]. This genome encodes six structural proteins: nucleocapsid (N), phosphoprotein (P), matrix protein (M), fusion protein (F), glycoprotein (G), and RNA polymerase [101]. The G protein enables viral attachment to host Ephrin-B2 and Ephrin-B3 receptors, while the F protein facilitates membrane fusion and viral entry into host cells [102, 103]. Fruit bats of the genus *Pteropus* serve as the natural reservoirs of NiV and are distributed across tropical and subtropical regions of Asia, East Africa, Australia, and certain island regions [104, 105]. Transmission occurs through direct contact with infected animal secretions, consumption of contaminated fruits, or close contact with infected individuals [106, 107] (Figure 3).

The emergence and spread of NiV are influenced by several anthropogenic factors. High population density increases human-environment interactions and facilitates transmission, particularly in densely populated regions such

as parts of South Asia [109, 110]. Deforestation and habitat loss force bats to migrate toward human settlements, often leading to spillover events via contaminated fruits or intermediate hosts such as pigs [106]. Notably, outbreaks in Malaysia (1998-1999) and Kerala (2016) have been associated with environmental changes such as drought and deforestation linked to El Niño events [111, 112]. Changes in reservoir distribution due to habitat loss also contribute to increased contact between bats and humans in urban areas [113, 114]. Additionally, cultural and socioeconomic factors, including bat hunting, livestock farming, and consumption of contaminated food products such as date palm sap, play important roles in transmission dynamics [115-118].

4.5. Rabies

Rabies is a long-recognized but often underreported zoonotic disease that affects the central nervous system and is almost invariably fatal once symptoms appear [119]. It is caused by a single-stranded RNA virus belonging to the *Lyssavirus* genus of the *Rhabdoviridae* family [120]. Despite the availability of effective vaccines, rabies continues to cause approximately 59,000 deaths annually worldwide [119]. The disease is endemic in many parts of the world, particularly in developing regions of Africa and Asia, where factors such as rapid urbanization, poor waste management, limited vaccination coverage, and inadequate hygiene contribute to its persistence [121, 122]. Rabies transmission occurs through both urban cycles—primarily involving domestic and stray dogs—and sylvatic cycles involving wildlife such as foxes, wolves, bats, raccoons, and skunks. These transmission cycles often overlap [119].

Although rabies can infect all mammals, only certain species act as reservoirs [124]. Domestic animals account for a smaller proportion of cases [125, 126]. Transmission primarily occurs through bites or saliva from infected animals, but can also occur via scratches, aerosols, organ transplants, or exposure to infected body fluids [119, 127]. Clinical symptoms include anxiety, confusion, hallucinations, and hydrophobia [128]. Environmental and social factors—including urbanization, deforestation, and waste accumulation—significantly contribute to the persistence and spread of rabies [129, 130].

4.5.1. Rabies and Urbanization

Urbanization, with over half of the global population now residing in cities, creates conditions that facilitate rabies transmission and complicate control measures [131]. Migration from rural to urban areas increases interactions between humans, domestic animals, and wildlife, raising transmission risks [130, 132]. Cases of bat-related rabies, once limited to rural regions, are now increasingly reported in urban settings [133]. Global travel and animal movement also contribute to disease spread. Travelers may encounter infected animals, with exposure rates estimated at 0.4 per 1000 individuals per month abroad [134, 135]. Additionally, the movement of animals—both intentional and accidental—can introduce rabies into previously unaffected regions [136-138].

Urban infrastructure and environmental features, such as roads and water canals, may further facilitate the spread of rabies by influencing animal movement and limiting access to vaccination services [131, 133, 139]. Structures like abandoned buildings and tunnels provide habitats for bats, increasing their population density in urban areas [133, 140].

4.5.2. Rabies and Garbage Accumulation

Increasing urban populations generate large amounts of waste, often exceeding the capacity of local management systems ^[141]. Improper waste disposal leads to the proliferation of stray animals, particularly dogs, which act as key rabies vectors ^[142, 143]. Open dumping sites provide food and shelter for animals such as stray dogs and raccoons, increasing their populations and the risk of disease transmission ^[130, 142, 144]. Dogs that rely on waste for food may become more aggressive, increasing the likelihood of human attacks and rabies exposure ^[145]. Effective waste management is therefore essential for controlling rabies transmission.

4.5.3. Rabies and Pets

Urbanization has also led to a rise in pet ownership, particularly of cats and dogs, which can increase rabies transmission risks if not properly managed ^[146]. Pet populations have grown significantly in many regions worldwide ^[121, 147-150]. Dog bites remain a leading cause of rabies transmission to humans ^[151]. Close human-pet interactions, especially in densely populated urban environments, increase exposure risks. Some pets roam freely or come into contact with wildlife, facilitating disease transmission ^[147]. Preventive measures such as vaccination, responsible pet ownership, and public awareness are crucial for reducing risks ^[130].

4.5.4. Rabies and Deforestation

Human-driven environmental changes—including deforestation, urban expansion, and resource extraction—have reduced natural habitats and increased contact between wildlife, domestic animals, and humans ^[122, 130, 154]. This increases the likelihood of rabies transmission. The global decline in forest area has contributed to wildlife displacement and adaptation to urban environments ^[155]. Bats, in particular, have established colonies near human settlements, increasing the risk of transmission through bites ^[122, 152]. Wildlife species such as raccoons have also adapted well to urban settings, further complicating disease control ^[158].

4.5.5. Rabies and Food Supply

Growing demand for food has led to an increase in livestock populations, creating environments that facilitate interspecies disease transmission ^[122, 130]. In some regions, livestock farming has been associated with increased attacks by hematophagous bats ^[159]. In addition, practices such as dog slaughter for consumption in certain countries increase exposure risks, particularly due to poor hygiene and limited awareness among workers ^[122]. These conditions highlight the importance of education and improved sanitary practices in reducing disease transmission.

4.6. SARS-CoV-2

SARS-CoV-2, the causative agent of COVID-19, emerged in December 2019 in Wuhan, China, and rapidly developed into a global pandemic ^[160, 161]. As of October 2022, hundreds of millions of confirmed cases and millions of deaths have been reported worldwide. Despite the implementation of control measures such as vaccination, lockdowns, testing, contact tracing, mask use, and social distancing, significant challenges remain in managing the pandemic ^[162].

Several anthropogenic factors have contributed to the spread of SARS-CoV-2. Wildlife markets, where humans and animals interact closely, are believed to have played a role in the initial transmission ^[163, 164]. Globalization, including international travel and trade, facilitated the rapid spread of the virus across borders, limiting the effectiveness of travel restrictions alone ^[165-168]. Urbanization and increasing population density also contribute to sustained transmission by enhancing human contact rates, particularly in densely populated areas ^[169].

5. Selected Bacterial Diseases

5.1. Leptospirosis

Leptospirosis is a widespread zoonotic bacterial infection that affects both humans and animals globally. Its broad distribution is largely due to the wide range of mammalian hosts involved in its transmission ^[170-172]. In addition to mammals, the causative organisms have also been identified in birds, amphibians, reptiles, and fish ^[173]. This disease represents a major cause of illness and death, particularly in tropical regions ^[171]. The infection is caused by *Leptospira* species, which are highly motile, spiral-shaped bacteria ^[174]. Transmission can occur either through direct contact with infected animals or indirectly via exposure to contaminated water, soil, or urine. The bacteria typically enter the human body through breaks in the skin or via mucous membranes such as those of the eyes, nose, or mouth ^[175]. Globally, leptospirosis is responsible for approximately 60,000 deaths each year ^[171]. Despite its significant impact, it has long been underrecognized and neglected. Recent studies indicate that the disease is re-emerging as a major public health concern, with increasing incidence rates and frequent outbreaks reported worldwide ^[176]. Cases have been documented in regions such as Nicaragua, Brazil, India, Southeast Asia, and the United States ^[177-184]. However, underreporting remains a concern, particularly in densely populated regions like South and Southeast Asia, where surveillance systems are often inadequate ^[171]. Several contributing factors influence the occurrence of leptospirosis. These include rapid urbanization, climate change, flooding, poverty, habitat destruction, and increased contact with animals such as rodents, dogs, and cats.

5.1.1. Leptospirosis and Urbanization

Urbanization has been a gradual process for centuries, but its global expansion has accelerated significantly in the 21st century, especially in developing regions of Asia and Africa ^[185]. Rapid population growth in cities often outpaces infrastructure development, resulting in overcrowded living conditions, particularly in informal settlements. Such environments are characterized by inadequate sanitation, poor waste management, limited access to clean water, and high rodent populations ^[186]. Rodents are considered the primary reservoirs of *Leptospira* ^[187], and their proliferation in urban settings increases human exposure ^[188]. Due to limited understanding of rodent ecology, controlling their populations remains a major challenge ^[189]. Studies have demonstrated high infection rates among urban rodent populations. For example, research in Baltimore, USA, found *Leptospira* in 95% of captured rodents ^[190], while prevalence rates in Switzerland range from 10% to 20% ^[191].

5.1.2. Leptospirosis and Extreme Weather Events

Urban expansion contributes to increased greenhouse gas emissions and climate change, which in turn influence rainfall patterns and extreme weather events^[192]. Alterations to natural drainage systems due to urban development can increase the likelihood of flooding^[176, 193]. Heavy rainfall, storms, and flooding events have been linked to higher leptospirosis incidence, as they facilitate the spread (انتشار) of contaminated water^[194, 195]. In Brazil, it was observed that for each millimeter increase in daily rainfall, leptospirosis cases rose by approximately 0.55% compared to the average^[196]. Additionally, rising temperatures may enhance the survival of *Leptospira* in the environment^[197].

5.1.3. Leptospirosis and Socio-Economic Factors

Socioeconomic conditions associated with urbanization, such as poverty, homelessness, and inadequate housing, significantly contribute to the spread of leptospirosis. Individuals living in slums or unstable housing conditions are at greater risk due to increased exposure to rodents and contaminated environments^[190, 198, 199]. The disease is also recognized as an important health issue in disadvantaged regions of Europe^[200]. Migration from rural to urban areas has further contributed to urban outbreaks in both developing and industrialized nations^[201]. For instance, prevalence rates of *Leptospira* infection have been reported at 16% in Baltimore residents and up to 30% among children in certain areas of Detroit^[202, 203].

5.1.4. Leptospirosis and Pets

Domestic animals, particularly dogs and cats, play an important role in the transmission dynamics of leptospirosis. Pet ownership is widespread, with significant proportions of households owning pets in regions such as the United States and Europe^[204, 205]. Dogs are recognized reservoirs of *Leptospira*, particularly for serovars such as *Leptospira canicola* and *icterohaemorrhagiae*, which are commonly included in vaccines. While vaccination has been effective in reducing transmission of these strains, emerging serovars such as *Leptospira autumnalis* and *pomona*—not covered by current vaccines—pose new risks^[206, 207]. Consequently, even vaccinated dogs may contribute to disease transmission^[176]. Evidence from Russia indicates that transmission from dogs has been a significant contributor to human leptospirosis cases in recent decades^[208].

5.1.5. Leptospirosis and Wildlife Animals

The encroachment of wildlife into urban and suburban areas increases the risk of pathogen transmission to humans. Urban expansion and habitat alteration allow wild animals easier access to food and shelter in human-dominated environments. Species such as wild boars, foxes, deer, martens, raccoons, and skunks are increasingly observed in suburban and even urban areas. Studies have demonstrated the presence of *Leptospira* in wildlife populations; for example, 18% of wild boars in Berlin suburbs tested positive for the pathogen^[209].

5.2. Lyme-Borreliosis

Lyme borreliosis, commonly referred to as Lyme disease, was first identified in Lyme, Connecticut (USA) in 1975 and has since been reported in North America, Europe, and parts of Asia^[210]. It is a tick-borne disease caused by several *Borrelia* species, which lead to a range of clinical

manifestations. Different *Borrelia* species are associated with specific symptoms. For instance, *B. garinii* and *B. bavariensis* are linked to neurological complications, *B. afzelii* causes skin conditions such as acrodermatitis chronica atrophicans, and *B. burgdorferi sensu stricto* is associated with Lyme arthritis^[211-214].

5.2.1. Borrelia spp. and Geographical Distribution

B. burgdorferi sensu stricto is the primary cause of Lyme disease in North America and Europe^[212, 215]. Additional strains have been identified globally, including in South Korea and Taiwan^[216, 217], and a novel species, *Borrelia mayonii*, was reported in the United States in 2016^[218]. In Europe, multiple *Borrelia* species are present, with *B. afzelii* and *B. garinii* being the most common. In Asia, most human-pathogenic species have been identified, with *B. garinii* predominating^[219, 220]. Ticks of the genus *Ixodes* serve as the primary vectors, transmitting the bacteria between hosts^[212, 221]. The distribution of Lyme disease is closely linked to the presence of both vectors and reservoir hosts. Different *Ixodes* species dominate in various regions, such as *I. scapularis* in the eastern United States, *I. pacificus* in the west, and *I. ricinus* and *I. persulcatus* in Europe and Asia, respectively^[222-224].

5.2.2. Impacts of Climate Change and Anthropogenic Activities on Lyme Disease

Ticks thrive in environments such as forests, grasslands, and urban green spaces, where humidity and temperature conditions support their life cycle^[225-227]. These habitats also support rodent populations, which serve as hosts for ticks^[228]. Climate conditions strongly influence tick activity and distribution, with seasonal patterns varying based on temperature and environmental factors^[229-233]. Climate change is expected to alter these patterns, contributing to the spread of Lyme disease by expanding suitable habitats for ticks^[226, 234].

Human activities also play a major role. In North America, most Lyme disease cases occur in regions that have undergone significant land-use changes^[235-237]. Increased deer populations and habitat fragmentation have further enhanced tick proliferation and human exposure^[216]. Projections suggest that climate change may expand the range of ticks northward into Canada while reducing their presence in southern regions^[238]. Understanding environmental and ecological factors is essential for predicting disease spread and implementing effective prevention strategies.

5.3. Tuberculosis

Tuberculosis (TB), caused by *Mycobacterium tuberculosis*, remains a major global health challenge. According to the World Health Organization, approximately 10.6 million cases were reported worldwide in 2021^[239]. The emergence of multidrug-resistant TB continues to complicate control efforts. Research has identified multiple indirect drivers of TB transmission, summarized as the “Triple Whammy”: (i) socioeconomic factors such as poverty, overcrowding, and high population density; (ii) health-related factors including smoking, malnutrition, and diabetes; and (iii) environmental factors such as climate change and rising sea levels^[240-243]. Climate change influences TB transmission through several pathways. Changes in rainfall patterns, extreme weather events, and reduced agricultural productivity can lead to

food insecurity and malnutrition, which is a major risk factor for TB, particularly in high-burden countries like India [241]. Additionally, displacement caused by environmental disasters can result in overcrowded living conditions, further increasing transmission risks [243]. Addressing the environmental and socioeconomic determinants of TB is essential for reducing its global burden. Efforts to improve food security, housing conditions, and climate resilience will play a key role in controlling and eventually eliminating the disease.

6. Preventions

Reducing the impact of human-driven (anthropic) activities on the spread of emerging and re-emerging diseases is highly complex and requires a comprehensive One Health approach. Effective prevention and control of current and future pandemics depend on strong global collaboration among governments, pharmaceutical industries, diagnosticians, epidemiologists, public health experts, vaccinologists, and both medical and veterinary professionals.

To successfully implement the One Health framework, several key actions are necessary

Recruiting and training qualified professionals with appropriate expertise

- Ensuring rapid and accurate diagnosis along with timely treatment for both human and animal infections;
- Advancing the development and distribution of vaccines for disease control in human populations;
- Conducting continuous surveillance of wildlife to identify and characterize potential disease reservoirs, along with monitoring individuals who interact with wildlife to better understand behavioral and environmental risk factors [160, 161].

Regular epidemiological surveillance at local, national, and global levels is essential for reducing risks and improving the control and prevention of zoonotic diseases. A detailed understanding of risk factors is critical for designing effective intervention strategies to limit the spread of pandemics.

However, scientific efforts alone are insufficient to drive meaningful change. While the scientific community can raise awareness and provide reliable evidence, real progress depends on decisive political action at international, national, and local levels. Several major challenges must be addressed. First, the continuous growth of the global human population—often overlooked due to ethical, economic, and cultural considerations—needs to be managed through appropriate policies. Second, economic disparities between nations force vulnerable populations to make environmentally harmful choices, sometimes reinforced by international economic practices such as resource exploitation agreements. Third, inconsistent political approaches to natural resource management and conservation undermine efforts to protect ecosystems. Public education and awareness are also critical in reducing the spread of diseases.

- Minimizing vector-to-human transmission by restricting vector access to food sources, protecting animal feed from contamination (e.g., by bats), and maintaining proper hygiene practices

- Reducing animal-to-human transmission by limiting contact with wildlife, and using protective equipment such as gloves and appropriate clothing when handling animals.
- Preventing human-to-human transmission through avoiding contact with infected individuals and maintaining regular hand hygiene.

7. Conclusions

Human-driven environmental changes play a decisive role in the emergence and re-emergence of infectious diseases. Future pandemics may be even more severe than those experienced in the past or present, as ongoing environmental degradation continues to push ecosystems beyond their limits. The destruction of biodiversity reduces natural barriers that typically limit pathogen spread, while simultaneously increasing interactions between humans and wildlife—conditions that favor disease emergence. To address these challenges, a coordinated and multidisciplinary One Health approach must be implemented globally, integrating human, animal, and environmental health strategies to effectively prevent and control future pandemics.

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