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Review Article

Impact of Global Climate-Change on Ecology of *Anopheles* Mosquitoes: A Systematic Review

Seyyed Ghavam Shafagh [1], ***Eslam Moradi-Asl*** [2], ***Marieh Mirzagholipour*** [3], ***Ali Salehi Sahlabadi*** [4,5], ****Sayed Vahid Esmaeili*** [6], ****Chiman Karami*** [2,7]

1. *School of Medicine, Iran University of Medical Sciences, Tehran, Iran*
2. *Arthropod-Borne Diseases Research Center, Ardabil University of Medical Sciences, Ardabil, Iran*
3. *Students Research Committee, School of Health, Ardabil University of Medical Sciences, Ardabil, Iran*
4. *Safety Promotion and Injury Prevention Research Center, Research Institute for Health Sciences and Environment, Shahid Beheshti University of Medical Sciences, Tehran, Iran*
5. *Department of Occupational Health and Safety, School of Public Health and Safety, Shahid Beheshti University of Medical Sciences, Tehran, Iran*
6. *Student Research Committee, Department of Occupational Health and Safety Engineering, School of Public Health and Safety, Shahid Beheshti University of Medical Sciences, Tehran, Iran*
7. *Department of Microbiology, Parasitology and Immunology, Ardabil University of Medical Sciences, Ardabil, Iran*

***Corresponding Authors:** Emails: chkarami.chiman@gmail.com, vahidesmaili1979@gmail.com

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Abstract

Background: This study investigated the impact of climate variables on the prevalence of malaria, a climate-sensitive infectious disease.

Methods: A systematic review was conducted on articles published from Mar 2000 to Aug 2023 in Persian and English languages. Overall, 10,731 articles were retrieved, and 58 studies were included in the analysis.

Results: Climate variables such as temperature, rainfall, and humidity play a significant role in predicting malaria outbreaks, with inconsistencies observed in different regions, including Iran. The study highlights the need for tailored preventive

Conclusion: Strategies and interventions to address the impact of climate change on malaria transmission. Enhanced health system resilience is essential to combat the anticipated rise in malaria cases in the future.

Keywords: Climate change; Global warming; Malaria; *Anopheles*

Introduction

Climate change is the greatest menace to global health in the 21st century (1). Climate change will harm global health in the coming decades, endangering billions with temperature rises surpassing 2 °C (2). Climate disasters caused 11,000 cases with 2M deaths and $3.64T losses. Daily: one disaster, 115 deaths, $202M losses (3). The impact of climate change has intensified in recent years, and the last two decades have been the warmest years on record (4). Climate change could cause 250,000 additional deaths yearly (5). Global temperature to rise by 2-5 °C, causing ex-

treme weather events (6). In 2015, climate change induced- disasters accounted for 19% of all disasters, which increased by 12% compared to the last century (7). Climate change impacts health through heat waves, floods, droughts, vector-borne diseases, disasters, and malnutrition. Low-income countries are most vulnerable, but high-income countries also face risks, as seen in the 2003 European heat wave (8).

The relationship between climate changes and contagious illness

Increase in climate-related disasters lead to more severe events due to contagious diseases (4). According to the Intergovernmental Panel on Climate Change (IPCC) report, contagious diseases are among the indirect effects of climate change (6). Emerging and recurring infectious diseases like Ebola, COVID-19, and others are current public health challenges (9). Contagious diseases increase due to climate change impacting micro-organisms and habitats (4). Global warming can shift mosquito distribution, causing disease outbreaks (10). Climate impacts disease transmission. Emerging diseases like malaria threaten global health and require prevention (11). Disease-free areas at risk due to climate change outbreaks (12). Various theories link climate change to vector-borne diseases, such as temperature effects, transmission season extension, and ecological shifts (13).

Relationship between Malaria and climate change

Malaria, deadliest arthropod-borne disease, may be affected by climate change (14). *Anopheles* mosquitoes spread malaria. Around 60 species can transmit human malaria at 20-30 °C (15). Four Plasmodium species evolved from common ancestor 60 million years ago (16). *Anopheles* mosquitoes, carriers of malaria, are sensitive to climate conditions (17). There are five (previously four) Plasmodium species that commonly infect humans, namely *Plasmodium falciparum*, *P. vivax*, *P. ovale*, *P. malaria*, and, very recently, *P. knowlesi* (18). Minimum temperature for *P. vivax* transmission is 15 °C (15). WHO reported 435,000 deaths from malaria in the world in 2018 (19). Malaria cases to reach 1.6M by 2030 and 1.8M by 2050 due to climate change (20). Changes in bioclimatic variables impact *anopheles* breeding habitats, altering malaria transmission (21). Mosquito development, survival, and disease transmission are affected by temperature. *Anopheles* species may adapt to climate changes, altering disease dynamics (22).

Malaria poses health risks during health system failures caused by extreme events. About 3.3 billion people globally are impacted annually (20). This figure is expected to increase as climate change-induced disasters are increasing. An increase in malaria cases was reported four to five times over non-disaster periods after the flood disaster in Mozambique in 2000 (23). After Costa Rica earthquake, malaria incidence spiked by up to 1,600 and 4,700% in affected areas due to human behavior and environmental changes (24). Long-term fluctuation in bioclimatic variables can change the geographical spread of malaria vectors and parasites (25). More research is needed on the undefined role of malaria in low-income countries like Iran. Areas with poor health facilities are highly vulnerable to outbreaks due to climate change (26). Iran is in West Asia, the seventeenth largest country globally. Over 80% in arid/semi-arid regions, annual rainfall 240mm (27). Iran's dry climate faces frequent floods causing infrastructure damage annually (28). The intensity of flash floods will increase in the future while average rainfall will decrease (29). The destructive floods have increased ten times in the last 50 years ago (30, 31). Iran's Department of Environment reported that 74% of 421 flood events occurred from 1981 to 2001, with increased frequency since. Multiple floods from 2001 to 2019 led to 19 infectious epidemics in spring 2019 (31, 32). Vector-borne diseases spread faster, raising infection risks significantly (33). About six decades ago, a third of Iran's population was infected with malaria (34).

In Iran, native cases of the disease have declined, with no indigenous cases in 2018 and 2019 (35). Malaria cases surged in 2022, with a fivefold increase compared to 2021, expected to be tenfold

higher in one Iranian province (36). According to the latest report on the state of malaria in 2022, 5677 cases of this disease have been recorded in Iran (36). Foreign nationals, heavy rains in neighboring areas, and rising malaria cases in Pakistan and Afghanistan contribute to disease spread. Increasing climate change leads to hydrological disasters like floods, disrupting healthcare and worsening social-environmental conditions (24). Post-disaster disruptions increase risk factors, exposing populations to malaria (28). Identifying malaria outbreak risks is crucial for assessing vulnerability and pinpointing health system needs to reduce exposure. Understanding disease spread risks from climate change is crucial for effective policies and interventions.

Materials and Methods

Study design

The study focused on the impact of climatic variables on malaria prevalence, including global climate change-related studies, hydrological events, and studies conducted in Iran. A systematic review following PRISMA guidelines was conducted to ensure accuracy and reliability.

Search strategy

The search strategy included Persian and English articles from 2000 to 2023 in reputable databases. Keywords related to climate change, global warming, malaria, and *Anopheles* mosquitoes were used. EndNote reference manager was utilized for article organization. Two independent reviewers screened search results for eligibility, with a third reviewer resolving any disagreements.

The inclusion and exclusion criteria

Studies were included according to the inclusion criteria in the following; Country (Iran and other countries), malaria (All studies addressing interactions between the human population and malaria vector, organism, or/and confirmed infected cases), the subjects of the studies investigated the climatic changes, language of studies (Persian and English) and availability of full text. Exclusion criteria included articles of unrelated, poor quality, published in non-English and Persian language, summary of the articles presented on conferences, and educational articles.

Quality assessment

Quality assessment was performed using an Epidemiology checklist, with a score of 20 or above deemed acceptable. Screening resulted in 58 articles meeting the inclusion criteria.

Article screening process and Data collection

The articles were categorized based on climate change impacts on malaria prevalence. Data collection involved 10731 initial studies, with 58 ultimately included in the review. The quality of documentation for findings was evaluated using the STROBE checklist. The review highlighted the impact of climate variables and disasters on malaria prevalence from 2000 to 2023.

Results

Findings from searching scientific databases revealed 10,731 articles. After removing duplicates, 7516 articles were identified, with 58 relevant studies selected for data extraction (Fig. 1). Of these studies, 33% were from Iran and 67% were from other regions, including Africa. The extracted articles were classified based on climate variables, study design, publication date, study area, discussions, findings, and global extreme events, with a focus on climate variables and disaster types in Iran.

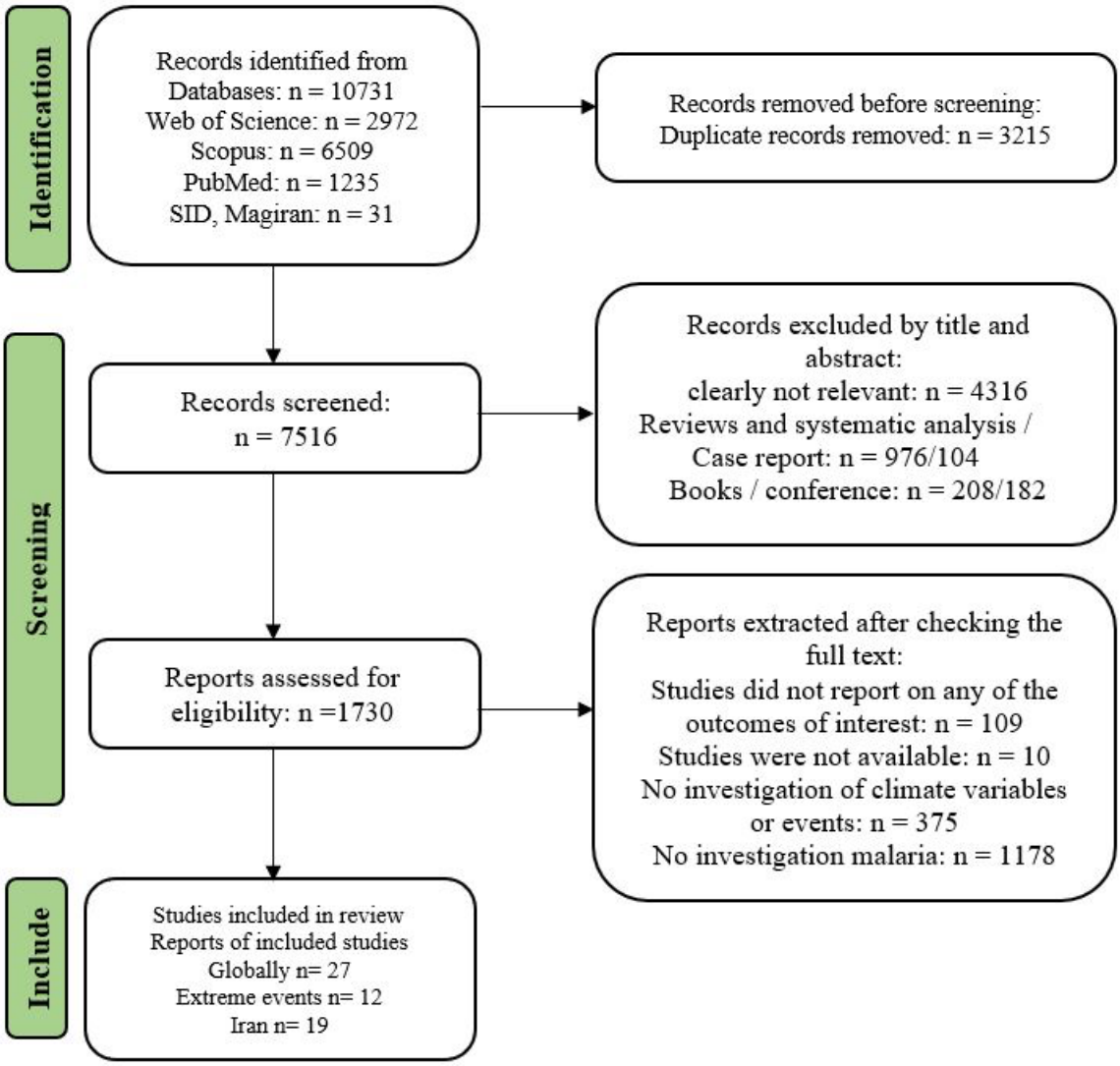

Fig. 1: PRISMA (Preferred Reporting Items for Systematic Reviews) flow diagram

Risk factors such as rainfall, temperature, extreme events, and floods play a significant role in malaria prevalence in Africa. Some studies point to a bell-shaped relationship between malaria intensity and temperature, with a peak at 28 °C (Table 1). Warmer climates are expected to worsen malaria conditions. While some research shows a positive correlation between rainfall and malaria cases in certain areas, others report a negative impact (Table 2). In Iran, an increase in temperature has been linked to a rise in malaria incidence (Table 3). Floods and rising temperatures due to global warming can also contribute to malaria outbreaks. High-altitude regions worldwide may see an increase in malaria transmission due to climate change.

Table 1: Characteristics of global articles on climate and Malaria

Study location	Short Title	Bioclimatic Variables	Conclusion	Ref
North-East India/ Mizoram 2023	Malaria hotspots in Mizoram, India-Bangladesh border.	Temperature, relative humidity and rainfall	Strong link between malaria cases, temperature, elevation and forest classes.	(21)
Burkina Faso 2023	Impact of weather on cause-specific deaths in rural Burkina Faso.	temperature and precipitation	Increased risk of death from malaria with high precipitation and temperature.	(25)
India/ Ahmedabad and Surat 2022	Urban malaria influenced by relative humidity.	relative humidity	relative humidity is a critical factor in the spread of urban malaria	(37)
Southern Africa 2021	Climate impact on malaria.	temperature and rainfall	Max temperature negatively correlated with malaria in all ages, while min temperature and mean rainfall negatively correlated. Max rainfall was positively correlated with malaria, significantly in older age group.	(38)
Ethiopi / Zuria 2021	Malaria epidemics linked to rainfall in Gondar, Ethiopia.	Rainfall and Temperature	Increased rain increased malaria transmission in Bulgaria.	(1)
Sweden 2021	Historical malaria cases in Sweden: climate-based analysis.	Temperature and precipitation	Malaria deaths depend on warm-season temperature, with non-linear response to precipitation.	(39)
India/ Pune 2020	Rainfall cutoff for malaria outbreaks in India.	rainfall	Variation in outbreak timing based on level of humidity and aridity.	(40)
Sri Lanka / Kataragama 2020	Impact of environment on malaria in Sri Lanka.	temperature, rainfall, and relative humidity	Environmental factors increased malaria in Kataragama 1991-1995 but not 1999-2001.	(41)
West Africa 2020	Climate Variability and Malaria over West Africa	Temperature and precipitation	High temps increase malaria transmission, followed by outbreaks after peak rainfall.	(42)
India 2020	Predicting Malaria using weather data.	Temperature, precipitation and humidity	Minimum temperature rise linked to increased malaria cases; no correlation found for temperature decrease.	(43)
Africa 2020	Climate change affects African Malaria.	Temperature	Highland areas have more malaria with higher temperatures. Sahel areas less affected by temperature increase for malaria.	(44)
South Korea 2019	Climate change impact on malaria transmission.	Temperature and precipitation	Climate change increases the prevalence of malaria	(45)
Kenya 2019	Predicting climate change impact on malaria in Kenya.	Temperature and precipitation (soil moisture)	Soil moisture up, air temp down, more malaria.	(46)
Burkina Faso 2019	Factors Malaria Hotspots Nanoro District. surveillance area, Burkina Faso	Temperature and precipitation	Rainfall, temperature linked to malaria cases with 9–14-week delay.	(47)
Uganda 2018	Climate and interventions impact malaria dynamics.	precipitation, temperature	Altitude and distance to water lower malaria rates. Higher temperatures and rainfall increase malaria risk.	(48)
China 2018	Malaria and weather in China.	Temperature, precipitation and humidity	1 °C rise in both max and min temp linked to 10.7% and 11.8% increase in malaria. Min temps more impact in cold season.	(2)
Indonesia 2018	Weather, migration, malaria in Purworejo, Indonesia.	Temperature, humidity and precipitation	1% higher humidity led to 10.47% lower malaria cases after 2 months; 1mm more rain caused 0.08%-0.09% increase in cases.	(49)
Nigeria 2018	Malaria Forecast in Nigeria.	Temperature, precipitation and humidity	Humidity, rainfall, and temperature affect malaria incidence. rain forest areas and positive in the higher and colder stations.	(50)
Zimbabwe 2017	Malaria trends in rural Zimbabwe.	Temperature and Precipitation	Minimum temperature linked to malaria after 1-2 months.	(51)
Mozambique 2017	Climate impact on malaria in Chimoio.	Temperature and precipitation	Mean temperature predicts Malaria, Rainfall 6-8 wk before is correlated.	(52)
Kenya 2017	Effect of climatic variability on Malaria trends in Baringo County, Kenya	Temperature and precipitation	Increased rainfall 2 months later raised Malaria transmission. Temperature rise led to more cases in riverine and highland zones.	(53)
Uganda 2016	Climate impact on malaria in Chimoio.	Temperature and precipitation	Rising heat, more rain boosts malaria.	(54)

Table 1: Continued…

Sub-Saharan Africa 2016	Impact of large dams on malaria in Africa.	Temperature	Large dams and climate change increase malaria.	(55)
Nepal 2013	Climate change impact on malaria.	Temperature, precipitation and humidity	No link between humidity and malaria. Higher temp increases malaria.	(56)
China 2012	Rainfall drives malaria resurgence.	Temperature, precipitation and humidity	PDL time series regression found only 1–2-month lag rainfall linked to malaria in study areas.	(57)
Korea 2012	Impact of climate on malaria in Korea.	Temperature, humidity and precipitation	Temperature rise increases malaria, humidity decreases.	(58)
Africa 2005	Lessons learned from malaria control in Africa for future perspectives.	Temperature and precipitation	Increase in malaria cases in warm, wet African highlands.	(59)

Table 2: Characteristics of global malaria disaster articles.

Study location	Title	Bioclimatic Variables	Conclusion	Ref
Eastern Africa 2023	Analysis of health priorities in Sino-Africa cooperation in Eastern Africa focusing on flooding and malaria burden in children.	flood	Flood occurrence and duration increased from 1990 to 2019 in E.A FOCAC partner countries, but had weak correlation with child malaria cases.	(3)
Ethiopia 2023	El Niño impacts malaria in Ethiopia. New adaptation tools	drought	Malaria outbreaks happen post-JAS rainy season, linked to El Niño events.	(60)
China 2014	Evaluation of malaria burden in flooded Mengcheng, China.	Flood	Flooding and waterlogging increase malaria risk during flood season.	(61)
Mozambique 2012	Post-flood Infectious Diseases in Mozambique	Flood	Floods increase malaria prevalence 4-5 times.	(23)
Costa Rica 2012	Post-Disaster Malaria in Costa Rica	Earthquake Flood	Significant rise in malaria cases post-earthquake.	(24)
Ethiopia 2009	Strengths and weaknesses of Gambella flood coping.	Flood	Flooding causes deaths, injuries, malaria, and diarrhea.	(62)
Zambia 2007	*Anopheles* arabiensis transmits *Plasmodium falciparum* after drought.	Drought	Decreased malaria cases due to drought, anopheles mosquito resurgence when rain returned.	(63)
Latin America 2006	Climate change impact in Latin America.	Cyclone, Flood, Drought	"Flooding spreads disease, rain clears breeding grounds, aids parasites.	(64)
Mozambique 2006	Malaria rapid tests post Mozambique flood.	Cyclone, Flood	"Flooding spreads disease, rain clears breeding grounds, aids parasites.	(65)
Dominican 2005	"Flooding and communicable diseases fact sheet."	Flood	2004 Dominican Republic flooding caused malaria.	(66)
South America 2002	The El Niño Southern Oscillation and malaria epidemics in South America	Flood and Drought	Flooding causes malaria, drought, delayed epidemics.	(67)
Sudan 2000	A study of the urban malaria transmission problem in Khartoum	Flood	Increased post-rainy season infections in area with higher risk of malaria epidemics after floods.	(68)

Table 3: General characteristics of the articles studied on climatic variables and Malaria in Iran, which were eligible for review

Study location and year of publication	Short Title	Bioclimatic Variables	Conclusion	Ref
Iran/ Kerman Province 2023	Climate change impacts malaria vectors distribution in Iran.	Temperature, precipitation and Altitude	Temperature important for malaria vectors.	(26)
Iran / Zahedan 2022	The effect of climate change on malaria transmission in the southeast of Iran	Temperature, precipitation	ANN study predicts malaria cases in Zahedan under climate change scenarios.	(27)

Table 3: Continued…

Iran 2022	Study on Malaria and Leishmaniasis in Iran.	earthquakes, floods, and droughts	Stable malaria rate before 1990 earthquake, decreased after disaster till 1997. 1997 disaster (β coefficient: -2.7; P = .001)	(28)
Iran / Kashan 2021	Meteorological factors affect mosquito population in Iran.	precipitation, relative humidity, wind speed and temperature	Weak negative correlation with humidity and rain, weak correlation with wind, strong with temperature.	(69)
Iran 2019	Climate Change and the Risk of Malaria Transmission in Iran	All 19 Bioclimatic variables (Bio 1-19)	Different environmental factors affect malaria vectors; high-risk areas are expected to decrease and shift.	(31)
Iran/ Sistan – Baluchestan 2018	Climate and Malaria in Iran.	Temperature, humidity, and precipitation	Malaria incidence linked to high temp, low rainfall, humidity (<60%).	(70)
Iran 2017	Spatial changes in the distribution of malaria vectors during the past 5 decades in Iran	All bioclimatic variables	Rainfall reduces malaria transmission by destroying larvae. Southern and eastern regions affected by monsoons.	(71)
Iran 2016	Meteorological factors and malaria in SE Iran.	precipitation, temperature, relative humidity	Rainfall correlates positively with malaria after 6-7 months.	(72)
Iran 2016	Impact of El Nino southern oscillation on annual Malaria occurrence in Iran	Precipitation	Characteristics of global articles on climate and Malaria.	(73)
Iran / Kerman 2016	Climate impact on Malaria in Kerman, Iran.	Temperature, Humidity and precipitation	Malaria incidence rises with higher monthly temperatures.	(74)
Iran / Kerman 2016	Impact of Climate and ENSO on Malaria in Kerman.	Temperature, precipitation and relative humidity	Malaria outbreaks are impacted by temperature, with decreased cases above 40°C.	(22)
Iran 2014	Climatic survey of malaria incidence in Iran during 1971-2005	Temperature, humidity and precipitation	Low correlation with disease outbreak.	(75)
Iran 2014	Assessment of malaria status in Iran	global warming, decreased precipitation, and drought	Disease transmission in southeastern Iran malaria decreased due to climate change.	(77)
Iran / Konarak 2014	The epidemiological features of malaria in Konarak, Iran (2007–2011)	Temperature, rainfall and floods	Highest malaria cases in 2007 linked to rainfall, floods, hurricane, and ponds.	(32)
Iran/Rudan 2014	Environmental Factors, Malaria Prevalence Rudan 2003-2011.	Precipitation, relative humidity and temperature	Negative correlation: Malaria vs. weather conditions.	(77)
Iran 2013	Survey of climatic condition of Malaria outbreak in Iran using GIS	Precipitation, humidity and temperature	Malaria rates drop with less rain and humidity.	(78)
Iran 2012	Spatial outline of Malaria transmission in Iran	Precipitation, relative humidity, temperature, altitude	Temperature affects malaria; humidity too.	(79)
Iran/ Chabahar 2012	Bioclimatic analysis of the Malaria outbreak in Chabahar	Temperature, humidity and precipitation	Disease incidence relates to average temperature variations, showing significance.	(80)
Iran/ Chabahar 2011	Impact of southern oscillation on malaria in Chabahar, Iran.	Rainfall and temperature	E1 Nino lowers malaria rates; La Nina raises malaria.	(33)

Discussion

This study explored the link between climate, hydrology, and malaria, comparing global trends with the situation in Iran. Climate change impacts hydrology, leaf litter quality and malaria vectors (71, 72). Factors affecting malaria from climate change (39). Seasonal malaria affected by culture; economy impacts community health behaviors. Poor sanitation, displacement, migration, prevention strategies, drainage, and environmental factors influence malaria occurrence (4, 26, 36).

Malaria parasite matures in 51 d at 18 °C, *Anopheles* mosquito lives up to 3 wk (2, 46). In 2005, *Anopheles* mosquitoes were observed at an altitude of 1,900 meters in the mountainous regions of Kenya for the first time (46). Malaria is usually found in lowland regions of western Kenya, with

little occurrence in the highlands of the Rift Valley. Malaria prevalence is higher during the dry season than the wet season. With an increase in temperature by just a few degrees, transmission could significantly increase. According to studies, malaria-endemic regions disappear above 1,800-2,000 m. Effective extrinsic incubation temperature is a limiting factor for survival. In Kerman, malaria decrease with rising temperatures. Similar findings reported (22, 26-28, 72, 74). Increased cases reported globally 1-4 months after rainfall under same climatic conditions due to less suitable environment for pathogen growth above 40 degrees (22, 49, 51, 53, 72). Mountainous regions are ideal for malaria carriers, especially after monsoon seasons increase outbreaks (44, 50, 53). Monsoon regions face higher risk of malaria after rains (1, 32, 33, 52, 57, 72).

Predictions based on climate scenarios in Iran show malaria vectors concentrated in border areas such as south, southeast, southwest, west, and northwest (33, 50, 55, 71, 73, 74, 79). Surprisingly, cases have emerged in previously malaria-free regions despite ongoing elimination efforts. Socioeconomic changes, health service access, and preventive measures during COVID-19 may increase malaria risk for one-third of Iranians in the future. The role of socio-economic conditions in malaria outbreaks is vital. Use of Shared Socioeconomic Pathways (SSP) scenarios can improve prediction reliability (14, 18, 26, 27). Studies show high-risk areas for malaria will decrease, but concern remains about disease vectors in new areas. Understanding the link between global malaria outbreaks, climate change, and effective response is essential for stakeholder.

Conclusion

Malaria and other infectious diseases will pose a health threat post-disaster, especially with rising temperatures and intense rainfall leading to outbreaks in non-malaria areas and mountain regions. Iran may experience more intense hydrological events, requiring better malaria control policies and comprehensive risk mapping.

Journalism Ethics considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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Conflict of interest

The authors declare that there is no conflict of interests.

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