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Research Article **Open Access**

Comparison of Climatic Suitability for *Aedes albopictus* Across Three Regions in Northwestern Libya

Nawal .A. Mahfoud [1] , Haifa M. Ben Miloud* [2]

[1] Department of Zoology, Faculty of Science, Tripoli University, Libya

***Corresponding author:** regcm00@Yahoo.com, Department of Atmospheric Science, Faculty of Science, University of Tripoli, Libya.

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Abstract

Every living organism is adapted to climatic conditions that support reproduction and survival in its environment. In this study, climate plays a crucial role in determining the climatic suitability of *Aedes albopictus* across three northwestern regions along the Libyan coast opposite southern Europe. This invasive mosquito species appears to have migrated across the Mediterranean Sea, reached the Libyan coast, and encountered suitable environmental conditions. Some of these areas contain shallow salt marshes and have favorable climatic conditions, as evidenced by the strong correlation between climatic factors and mosquito populations at a statistical significance level of p = 0.01. Although mosquito populations are low, Souq al-Juma has the highest number, followed by central Tripoli, while Tajoura has the lowest during the first period (1986–2025). In contrast, the Tajoura region appears more homogeneous and consistent in its population values, with a narrower distribution, indicating relative stability. This relative stability, together with favorable environmental conditions, may make the region more susceptible to future invasion by *Aedes albopictus* mosquito species.

Keywords: *Aedes Albopictus*, Climate Change, Climatic Suitability, Heat Map, Libya.

INTRODUCTION

According to the World Health Organization (WHO, 2020), vector-borne diseases account for more than 17% of all infectious diseases globally, causing over 700,000 deaths annually. Among these vectors, *Aedes albopictus* plays a critical role in transmitting viral pathogens such as dengue, chikungunya, and Zika, posing a threat to more than half of the world's population (Lambrechts et al., 2010; Kraemer et al., 2019). The Asian tiger mosquito has also spread widely due to favorable climatic and environmental conditions; its ability to produce dormant eggs enables it to survive in both tropical and temperate regions (Gratz, 2004; Hanson and Craig, 1995). Drought-resistant eggs are easily transported via shipping, used tires, and plant material (Caminade et al., 2012; Reiter & Sprenger, 1987; Fischer& Beierkuhnlein, 2010; Lounibos, 2002). According to the World Health Organization, 17% of infectious diseases are caused by *Aedes albopictus* mosquitoes, which are vectors of diseases with painful bites that threaten more than half of the world's population (Derraik, 2004; Lambrechts et al., 2010). Human-assisted dispersal and climatic fluctuations affect the survival and spread of these invasive species (Sharov et al., 1995; BenDor et al., 2006; Robinet et al., 2009). Among the climatic extremes that affect the survival of *Aedes albopictus* and the duration of egg dormancy are extremely high temperatures that prevent egg diapause (Pumpuni et al., 1992), whereas lower temperatures can induce egg diapause in many areas, including the southern United States (Lounibos et al., 2003). Moreover, rainfall and humidity are essential conditions for the stability of this species, as they ensure the survival of eggs and provide breeding habitats (Juliano et al., 2002). In previous studies, *A. albopictus* habitats in the Mediterranean region receive more than 500 mm of rainfall annually (Mitchell, 1995). Therefore, temperature, humidity, and rainfall are key environmental factors determining the distribution patterns of mosquito species (Elith and Lithwick, 2009). Climate projection models are important tools in ecological research. Several studies have provided important insights into the biodiversity of *Aedes albopictus* and changes in its distribution. By incorporating potential future climate trajectories and predicting environmental responses under different climate scenarios, these models are essential for assessing ecosystem services and conserving biodiversity (Thuiller, 2003; Araújo et al., 2005). Studies using historical and projected climate data indicate increased suitability for *Aedes albopictus* in several regions, including northern and central Europe, and limited its spread in southern Europe during the summer due to heat and drought (Caminade et al., 2012). Regional climate models during the 21st century predict that climate change will gradually expand the suitability of *Aedes albopictus* from western and central Europe to eastern Europe (2011–2100). GIS has also been used to analyze the spatial distribution of mosquito species (Pereira & Itami, 1991; Medlock et al., 2006; Betenedict et al., 2007; ECDC, 2009; Fisher et al., 2011), and to integrate climatic factors more comprehensively and accurately (Leathwick & Elith, 2009). Reports by the European Centre for Disease Prevention and Control (ECDC) and specialized modeling studies indicate that the rise in temperature due to climate change may strengthen the survival of the *Aedes albopictus* mosquito and expand its distribution range (Benedict et al., 2007; Medley, 2010; Woodward et al., 2001). Climate models predict that, as a result of climate change, the *Aedes aegypti* and *Aedes albopictus* mosquitoes will expand their range in the Northern Hemisphere and become extinct in the Southern Hemisphere. Vector-borne diseases are expected to spread in Europe as climatic conditions become more suitable (Laporta et al., 2023). Optimal temperature, sufficient rainfall, and relative humidity are considered key environmental factors influencing the availability of aquatic breeding sites and the success of mosquito life cycles, making them essential for mosquito survival and development (Bilal and Jebanesan, 2022). Temperature- and rainfall-based models provide additional evidence of the critical role of climatic factors in regulating the population dynamics of *Aedes albopictus* (Tran et al., 2013). Climate projections for the period 2070–2100 indicate that reduced precipitation rates may limit the presence of *Aedes albopictus* in lowland areas, while higher temperatures in upland and temperate regions may enhance the development and population density of these species, potentially supporting broader expansion in these environments (Lamy et al., 2023). A study conducted in the United Kingdom indicated that dynamic predictive models, which consider a range of climatic and environmental variables such as daily temperature fluctuations, precipitation levels, photoperiod, and human population density, suggest that most areas of the UK are currently unsuitable for the establishment of *Aedes albopictus*. However, future climate projections suggest that climate change may improve habitat suitability across large parts of England over the next five decades (Metelmann et al., 2019).

Climate change and human movement significantly influence the global distribution of the *Aedes aegypti* and *Aedes albopictus* mosquitoes, particularly in regions like Europe and the United States, due to the movement of goods (Kraemer et al., 2019). Furthermore, *Aedes aegypti* is notable for its ability to spread over relatively long distances. Observations conducted in several urban areas of central, southern, and coastal California between 2011 and 2015 revealed substantial expansion of both species, demonstrating their high ecological resilience and ability to adapt successfully to urban environments (Metzger et al., 2017). Several studies using machine-learning models indicate that climatic shifts as well as socio-economic changes may contribute to the global expansion of *Aedes albopictus*, potentially increasing the number of people at risk of vector-borne diseases to over one billion by mid-century, particularly in the United States, Europe, and India (Georgiades et al., 2023).

Study objectives

1. To examine temperature variations (summer and winter) and precipitation patterns in order to assess mosquito breeding and stability over a time series (1986–2025).
2. To produce maps and distribution outputs illustrating the environmental and climatic suitability for mosquitoes in the study areas.
3. To use future climate-model scenarios to assess future trends in climatic suitability and changes in mosquito density and distribution probability across the three regions.
4. To identify the areas with the greatest environmental and climatic stability conducive to future mosquito establishment.

MATERIALS AND METHODS

Data from Copernicus climate models were used to estimate the abundance of *Aedes albopictus* mosquitoes across Europe and along the Mediterranean coast. Three regions along the western Libyan coast were selected: Tripoli Center, Souq Al-Juma, and Tajoura. Climate-scenario data for 1986–2085 were obtained from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). Precipitation and temperature data for 1986–2025 were obtained from NASA Giovanni (https://giovanni.gsfc.nasa.gov). Tripoli Center is located in the western region of the country at a rocky headland overlooking the Mediterranean Sea opposite the southern coast of Sicily. Souq al-Juma lies east of Tripoli Center and is considered the largest district within Greater Tripoli. Tajoura lies east of Souq al-Juma and covers a comparatively large area, as shown in Figure 1. Table 1 summarizes the coordinates and elevations of the study areas (Libya's Popularities, 2009).

Table (1). Study areas, latitude, longitude, and elevation above sea level

Region	Lat	lon	Elevation above sea level
Tripoli center	32.87-32.93	13.17-13.22	11m
Souq Al-Juma	32.85-32.92	13.21-13.32	8 m
Tajoura	32.60-32.89	13.27-13.60	6 m

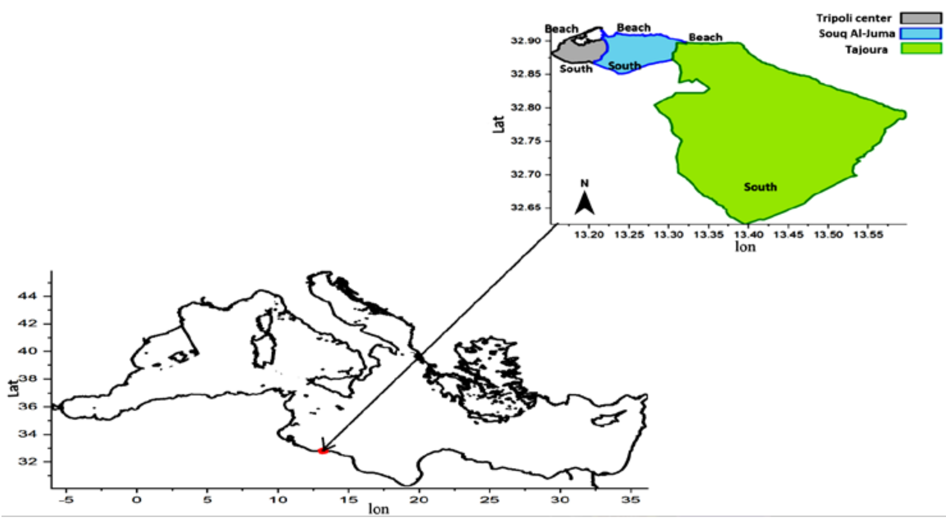

Figure (1). Study Area

Each region was divided into three zones: the entire area, the southern area, and the coastal zone. The climatic suitability data and calculations are shown in Table 2.

Table (2). Climatic suitability thresholds for survival

Climate Variables	Maximum Suitability Thresholds	Zero Suitability Thresholds (Unsuitable)
Annual Precipitation (P)	$P \geq 800$ mm	$P < 450$ mm
Summer Temperature (T_{summer})	$20°C \leq T_{summer} \leq 25°C$	$T_{summer} < 15°C$ or $T_{summer} > 30°C$
Winter Temperature (T_{winter})	$T_{winter} > 3°C$	$T_{winter} < -1°C$

Climatic suitability maps were generated by combining individual suitability layers using a linear additive method. Each factor was assigned equal weight and combined using the following equation [(ECDC 2009)]:

$$y = \sum a_i x_i$$

$where\ a_i = weight,\ x_i = factor(Tmax, Tmin,$ precipitation)

For equal weighting, $a_i = \frac{1}{3} \approx 0.333$, yielding the composite index

The resulting composite index was used to generate a suitability map for *Aedes albopictus* across the three study regions on the western coast of Libya.

RESULTS AND DISCUSSION

Tripoli Center and Souq al-Juma have humid coastal climates because of their proximity to the Mediterranean Sea, as does Tajoura. Tajoura is the largest of the study regions; part of it overlooks the sea, while a larger portion extends southward from the coast, as shown in Figure 1.

Statistical Analysis of Climatic Factors and *Aedes albopictus* Mosquito

Analysis of the time series of climatic factors, namely summer and winter temperatures (C^O) and total precipitation (mm/year), for the period 1986–2025, revealed that the Souq al-Jum'ah area is very similar to Tripoli Center in terms of these climatic factors, whereas Tajoura exhibits lower values, as shown in Figure 2.

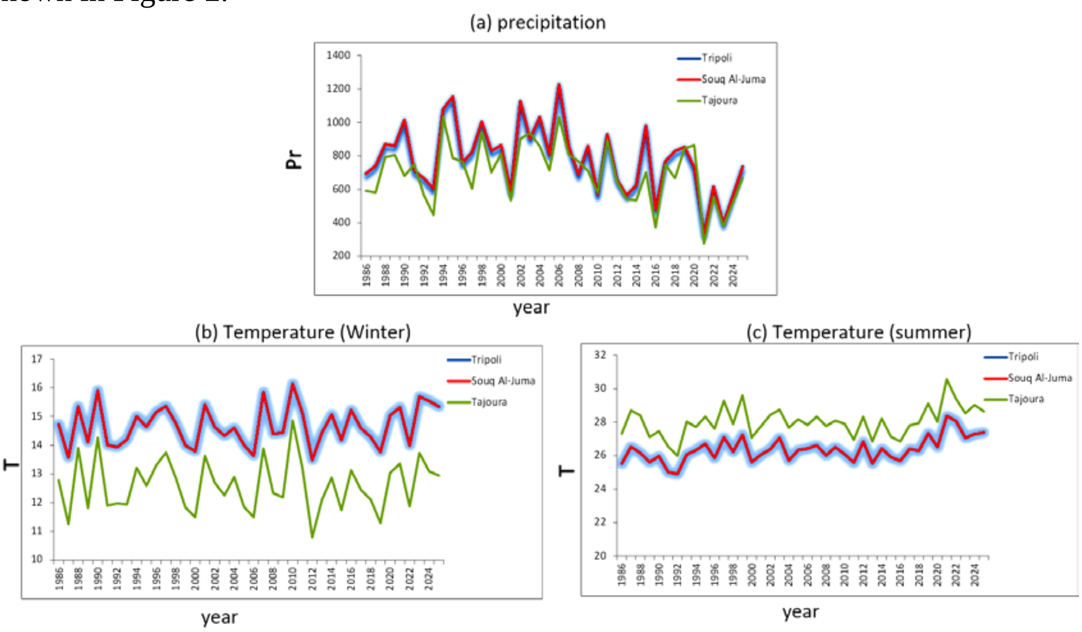

Figure (2). Time series of climatic factors: (a) rainfall, (b) winter temperature, and (c) summer temperature for three areas: Tripoli Center, Souq al-Juma, and Tajoura, for the period 1986-2025.

Pearson correlation analysis was used to examine associations between mosquito abundance and climatic factors—precipitation and summer and winter temperatures—during 1986–2025 and to assess climatic suitability according to Table 2. Figure 3 shows the relationship of each climatic factor with mosquito abundance. The results showed weak, statistically insignificant correlations ($p > 0.01$), as evidenced by weak positive correlations between mosquito populations and rainfall in Souq al-Juma and Tripoli Center and between mosquito populations and summer and winter temperatures in Tajoura. Conversely, there was a weak negative correlation between summer and winter temperatures in the Souq al-Juma and Tripoli Center areas and between rainfall and mosquito populations in the Tajoura area. These values were not interpreted because the effect of each factor in isolation could not be assessed reliably. These areas are coastal, as noted above, and also have high population densities. Some areas, like Tajoura and some neighborhoods in the Souq al-Juma area, have substantial vegetation cover. During winter, rainfall increases, creating pools suitable for mosquito breeding. Therefore, the factors were subsequently considered together to assess their combined relationship on larval development and mosquito reproduction. The values below show moderate to strong correlations at a statistically significant level ($p = 0.01$) between mosquito abundance and the climatic factors considered. In Tripoli Center, the strongest correlation is observed with winter temperature, reaching ($r=0.53$, $p < 0.01$), while in Souq al-Juma it reaches ($r=0.74$, $p < 0.01$). The impact of rainfall is also evident, reaching ($r=0.46$, $p < 0.01$). Meanwhile, the correlation with winter temperature in Tajoura reaches 0.54, and the combined effect of rainfall and temperature in summer is approximately($r= 0.36$, $p < 0.01$).

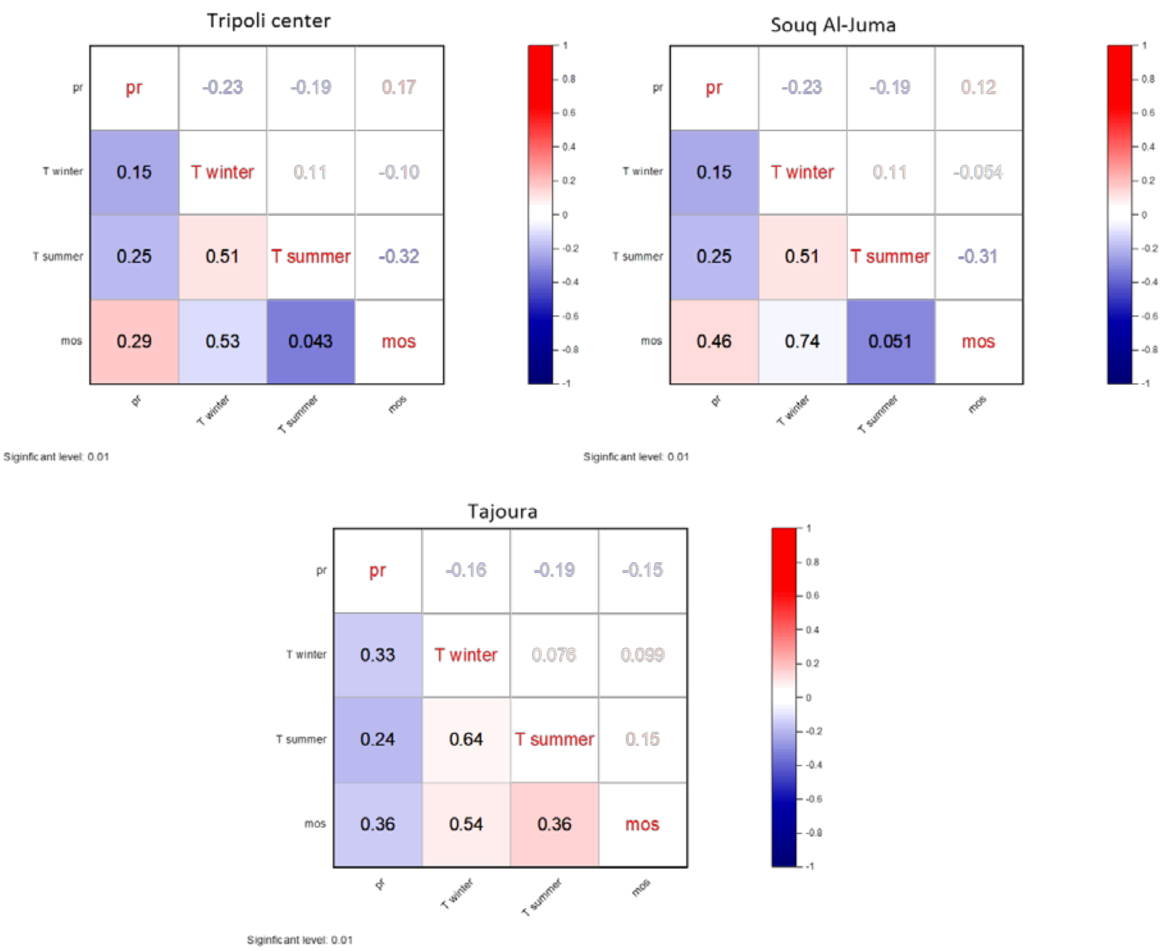

Figure (3). Correlation matrix between climatic factors (precipitation, summer temperature, winter temperature) for three areas: Tripoli Center, Souq al-Juma, and Tajoura, for the period 1986-2025.

Spatial Analysis of *Aedes albopictus* Mosquito

Using data from climate models, a spatial analysis of mosquito presence was conducted in three coastal areas of northwestern Libya. Although modeled mosquito abundance during 1986–2025 was lower than that reported for the Al-Bayda area in a previous study (Mahfoud & Ben Miloud, 2024) their presence was clearly concentrated along the coast. Souq al-Juma and Tripoli Center are more coastal than Tajoura, which covers a large area, part of which extends south of the coast and is characterized by vegetation cover. An increase in modeled mosquito abundance was observed during 2026–2085, as illustrated in Figure 4, based on climate scenarios.

Figure 5 presents box plots showing the range of values during 1986–2085 for the entire study areas, the coastal zones, and the southern zones. Souq al-Jum'ah was found to have the highest mosquito density in Figures 5 a–c, followed by Tripoli Center, while Tajoura showed the lowest. The data reflect greater dispersion in the Souq al-Juma area compared to other areas, indicating that more diverse environmental conditions and population density influence mosquito breeding.

In contrast, the Tajoura area appears more homogeneous and consistent in its values, with a narrower distribution, suggesting relative stability under the area's favorable environmental conditions for future mosquito breeding.

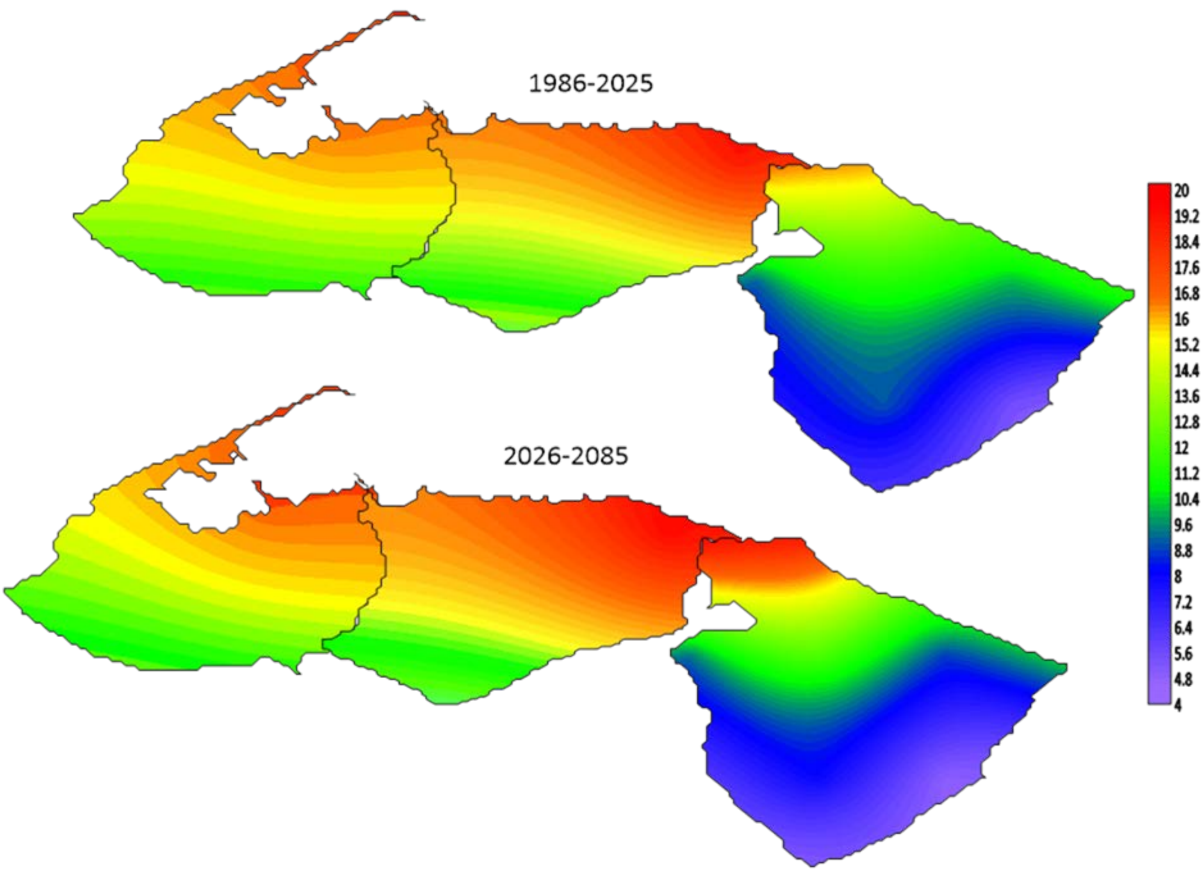

Figure (4). Spatial Distribution of *Aedes albopictus* Mosquitoes in Three Regions (Tripoli Center, Souq Al-Juma, and Tajoura)

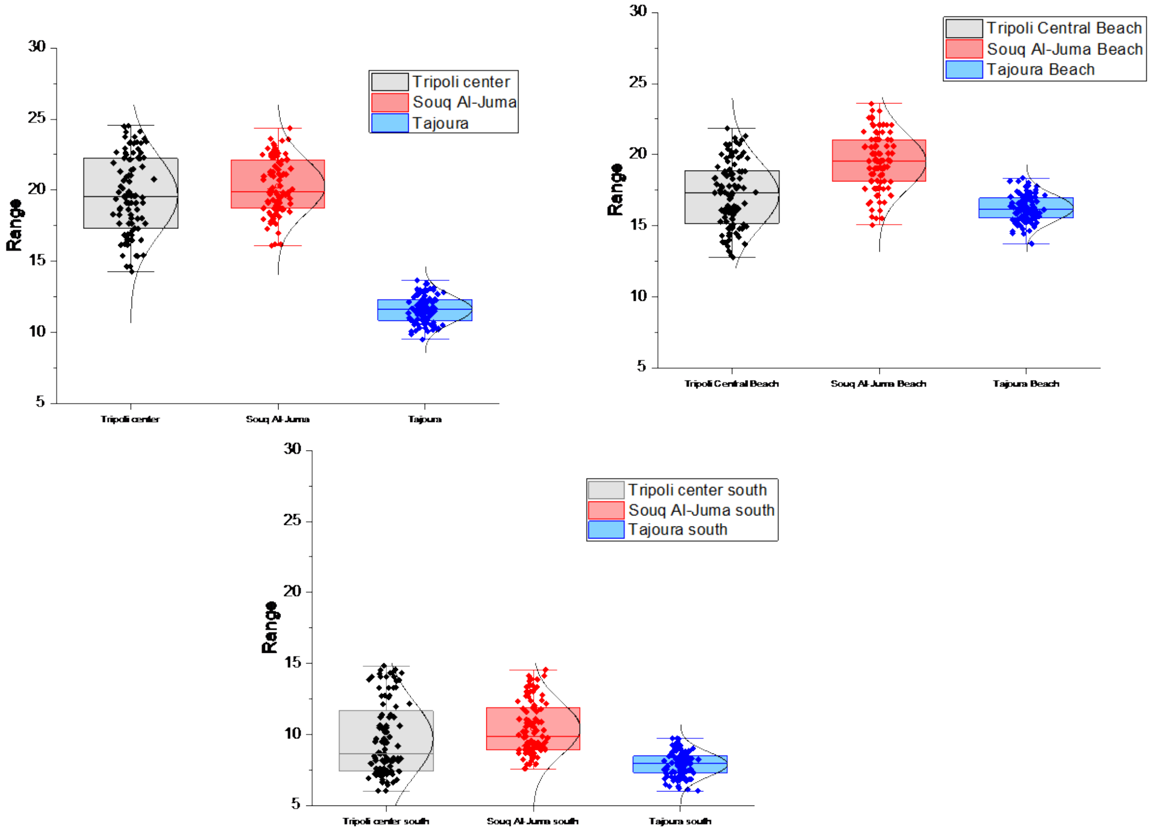

Figure (5). Distribution of *Aedes albopictus* in three areas (Tripoli Center, Souq al-Juma, and Tajoura): (a) entire area, (b) coastal zone, and (c) southern zone

Figure 6 presents heat maps of modeled mosquito abundance under climatic suitability conditions across the three regions during 1986–2085. In Tripoli Center, modeled mosquito abundance decreases during 1986–2000 and then gradually increases from 2000 through 2085. A similar pattern occurs in Souq al-Juma, but with higher values than in Tripoli Center.

This may reflect the presence of ponds and salt marshes in Souq al-Juma, whereas the Tajoura heat map shows an increase during 2000–2020 followed by a decrease during 2025–2085. When considering the probability density functions for mosquito climatic suitability during 1986–2025 and 2026–2085, as shown in Figure 7, Tripoli Center shows a wider distribution than Souq Al-Juma and Tajoura but a lower density. Souq Al-Juma has a narrower distribution than Tripoli Center, while Tajoura has more tightly clustered values and a higher density, as shown in Figure (7a).

Under future climatic and environmental conditions, modeled mosquito abundance in Tajoura is higher than in Souq Al-Juma and central Tripoli, according to the climate scenarios for the period 2026-2085, as shown in Figure (7b). Although the study area experiences hot, humid summers and cooler winters, modeled mosquito abundance is currently decreasing. Under future scenarios, climatic conditions may become increasingly suitable for mosquito breeding despite the species being non-native to the region.

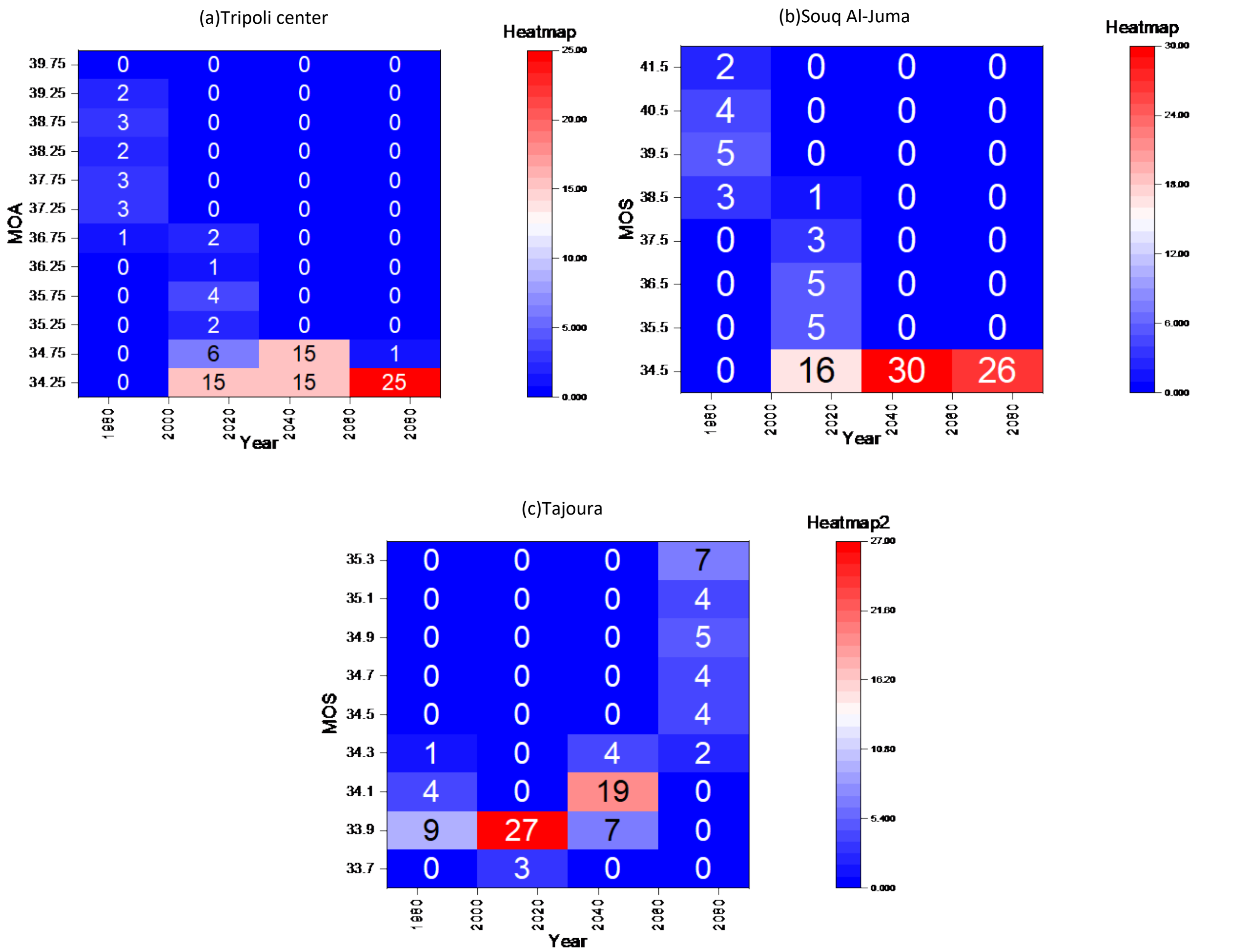

Figure (6). Heat map of climatic suitability for the *Aedes albopictus* mosquito for three regions: (a) Tripoli Center, (b) Souq al-Juma, (c) Tajoura.

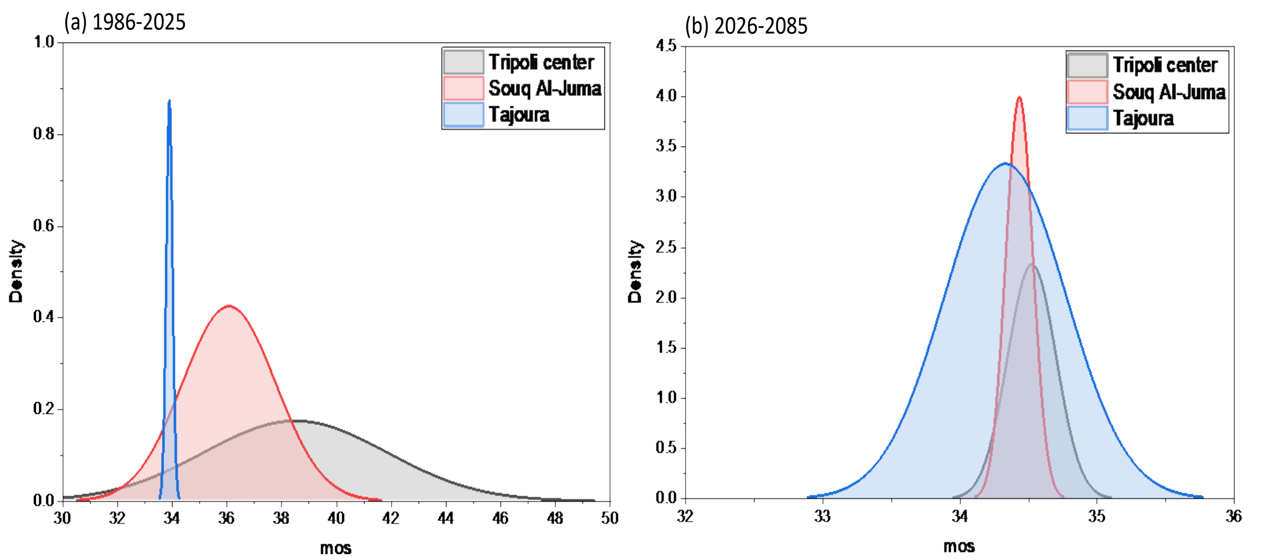

Figure (7). Density functions of climatic suitability for *Aedes albopictus* during 1986–2025 and 2026–2085 for three areas: Tripoli Center, Souq al-Jum'a, and Tajoura under future climate scenarios

Considering the standard deviation of climatic suitability, as shown in Figure 8 for the two periods, during the first period (1986-2025), the Souq al-Jum'ah area showed greater suitability than Tripoli Center. This suitability then decreased after 1995, with Tajoura being the least suitable area, as shown in Figure (8a). During the second period (2026-2085), as shown in Figure (8b), suitability decreases in Souq al-Juma and Tripoli Center, in contrast to the first period (1986-2025). A gradual increase in suitability is observed in the Tajoura area, due to climatic conditions, environment, and vegetation cover conducive to future mosquito breeding.

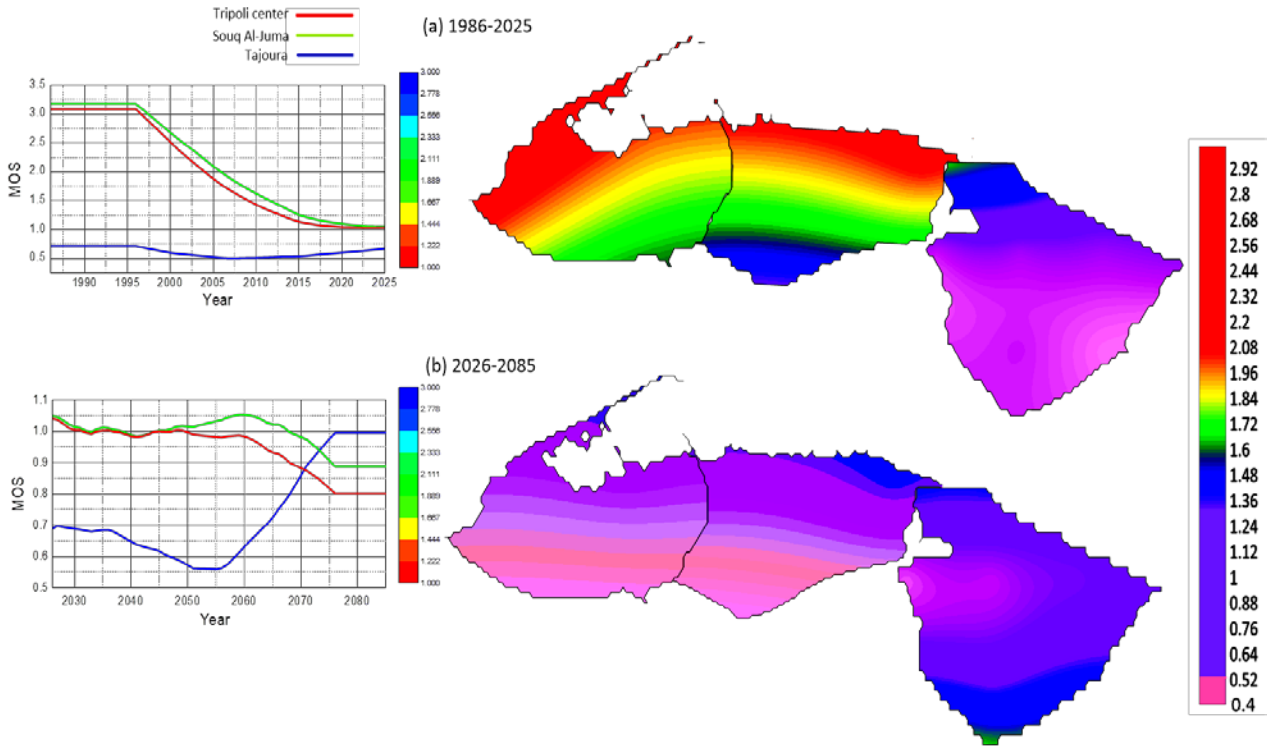

Figure (8). Standard deviation of *Aedes albopictus* suitability for the periods 1986-2025 and 2026-2085 for three areas: Tripoli Center, Souq al-Jum'a, and Tajoura under future climate scenarios

CONCLUSION

Climate plays a significant role in the biodiversity of the environment, particularly in the spread of disease-carrying mosquitoes. In recent years, numerous fever cases have been reported in association with environmental and climatic changes. Accordingly, increasing attention has been directed toward climate-related drivers of disease risk. This study focused on three closely situated areas in northwestern Libya: Tripoli Center, Souq Al-Juma, and Tajoura. Statistical analysis of the correlation matrix indicated moderate to strong correlations ($p = 0.01$) between mosquito abundance and the climatic factors considered. In Tripoli Center, the strongest correlation is with winter temperature, reaching 0.53, while in Souq Al-Juma it reaches 0.74. The impact of rainfall is also evident, reaching 0.46. Meanwhile, the correlation with winter temperature in Tajoura reaches 0.54, and the combined effect of rainfall and temperature in summer is approximately 0.36. Climate scenarios were also used to estimate *Aedes albopictus* abundance and climatic suitability. Across 1986–2085, Souq Al-Juma showed the highest modeled mosquito abundance, followed by Tripoli Center, while Tajoura showed the lowest values. The data show greater dispersion in Tripoli Center during 1986–2025, whereas the pattern differs during 2026–2085; a gradual increase in suitability is observed in Tajoura because of climatic conditions and vegetation cover that may favor future mosquito breeding. Overall, spatial variations in mosquito abundance are linked to the climatic and urban characteristics of each area.

This study successfully achieved its primary objective by modeling and characterizing the current and future climatic suitability of the *Aedes albopictus* mosquito across three coastal areas in northwestern Libya. By integrating historical climate data and future scenarios using an equal-weight linear additive composite index , our findings address the fundamental research question concerning spatial variations in mosquito spread risk. Specifically, the evidence points to a spatial shift in adaptation—from historical hotspots in Souq Al-Juma and central Tripoli toward greater ecological stability and higher breeding potential in Tajoura under future climatic scenarios.

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