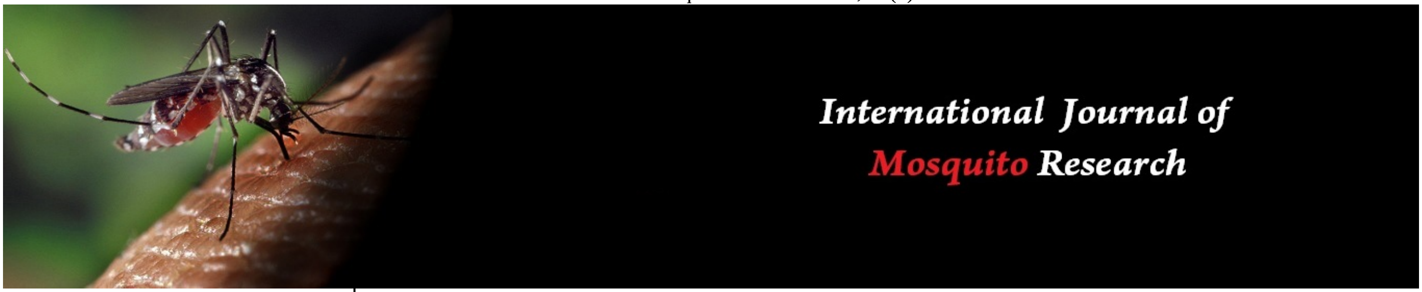

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Mosquito diversity and disease transmission in Kerala: An integrated review of species ecology, habitat, and public health impact

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Abstract
Mosquitoes are a highly diverse insect group with significant implications for both ecology and public health, particularly in Kerala, India. This review provides a comprehensive overview of mosquito species diversity in Kerala, detailing key vector genera such as *Anopheles*, *Aedes*, and *Culex*, as well as non-vector species that contribute to local ecological dynamics. Factors such as monsoon seasonality, diverse ecosystems-from coastal plains to high-altitude regions-and human-induced habitat alterations critically influence mosquito breeding and distribution patterns. Additionally, we explore species-specific habitat preferences and breeding behaviours that impact the transmission dynamics of mosquito-borne diseases like *Dengue*, malaria, chikungunya, and Japanese encephalitis, all of which pose major health challenges in the region. Understanding the complex relationships between mosquito ecology, climatic variations, and disease outbreaks provides critical insights into the regional epidemiology of mosquito-borne diseases. This review synthesizes ecological and epidemiological perspectives to advance our understanding of the role mosquito diversity and habitat specialization play in disease dynamics in Kerala.

Keywords: Mosquito diversity, habitat preferences, disease outbreaks, vector ecology, Kerala ecosystems, mosquito-borne diseases

Introduction

Mosquitoes, belonging to the *Culicidae* family, stand out as one of the most widespread and medically consequential insect taxa globally [1]. Found across diverse landscapes, from tropical rainforests to Arctic regions, these minute creatures wield significant influence over human health, ecology, and socioeconomic landscapes. Investigating their diversity is imperative for unravelling their ecological roles, evolutionary trajectories, and the intricate dynamics of mosquito-borne diseases. The sheer diversity of mosquitoes is staggering, with over 3,500 recognized species and numerous others awaiting identification [2, 3]. These species exhibit a broad spectrum of morphological, behavioural, and physiological adaptations enabling them to thrive in various ecological niches [4]. From benign nectar-feeders like *Toxorhynchites* to disease vectors such as *Aedes aegypti* and *Anopheles gambiae*, mosquito diversity not only fascinates but also carries profound implications for public health and vector management strategies [5, 6].

A hallmark of mosquito diversity lies in their habitat specialization. While some species excel in urban settings, breeding in artificial containers and polluted waters, others are restricted to pristine environments like freshwater marshes and tropical tree holes. This habitat preference reflects millennia of co-evolution with hosts, competitors, and predators, shaping their ecological niche breadth and distribution patterns [7, 8, 9, 10]. Furthermore, the intricate ecological interplay between mosquitoes and other organisms underscores the importance of understanding their diversity [11]. Mosquito larvae constitute a vital food source for various aquatic organisms, contributing to freshwater ecosystem dynamics. Conversely, adult mosquitoes take part in pollination and nutrient cycling, emphasizing their ecological significance beyond disease transmission [11-13]. Genetic diversity within mosquito populations significantly influences the transmission dynamics of mosquito-borne pathogens [14].

Variations in vector competence, host preference, and insecticide resistance among species and populations can dramatically alter disease epidemiology, impacting public health outcomes. Hence, unravelling genetic and phenotypic diversity is pivotal for devising effective disease control measures [15, 16].

In essence, investigating mosquito diversity spans multiple disciplines, encompassing entomology, ecology, epidemiology, and evolutionary biology. By elucidating species distributions, evolutionary relationships, and ecological interactions, researchers gain critical insights into disease dynamics, facilitating the development of innovative control strategies. A holistic understanding of mosquito diversity is indispensable for safeguarding public health, preserving biodiversity, and fostering sustainable coexistence with these influential insects.

Mosquitoes as Vectors

According to WHO, vectors are living organisms that can transmit infectious pathogens between humans, or from animals to humans. Many of these vectors are bloodsucking insects, which ingest disease-producing microorganisms during a blood meal from an infected host (human or animal) and later transmit it into a new host, after the pathogen has replicated [17]. Mosquitoes play a critical role as vectors in the transmission of various pathogens, making them significant threats to public health worldwide [18]. Vector incrimination of mosquito-borne diseases involves identifying the mosquito species responsible for transmitting a disease in nature. This is primarily achieved by detecting pathogens within the mosquito species. However, mosquitoes that do not bite humans or are not present in sufficient numbers are not necessarily considered as vectors [19]. As blood-feeding insects, mosquitoes serve as intermediaries for a multitude of disease-causing microorganisms, including viruses, parasites, and bacteria. Through their biting behavior, mosquitoes can acquire pathogens from infected hosts and subsequently transmit them to susceptible individuals during subsequent blood meals [20, 21]. This vector role is particularly pronounced in the transmission of diseases such as malaria, *Dengue* fever, Zika virus, yellow fever, and chikungunya [22].

The ability of mosquitoes to act as vectors is facilitated by their unique feeding habits and life cycle. Female mosquitoes require blood meals for egg development, driving their quest for hosts and subsequent transmission of pathogens [23]. During a blood meal, mosquitoes can acquire pathogens from infected hosts, including viruses, bacteria and protists [24].

Mosquito vectors exhibit distinct ecological preferences and behavior patterns that influence disease transmission dynamics. Many of these species are adept at breeding in urban environments and can transmit viruses between humans during blood-feeding. Understanding the specific vectorial roles of different mosquito species is essential for implementing targeted control measures, such as vector surveillance, habitat management, and the development of vaccines or vector control strategies aimed at interrupting the transmission cycle and mitigating the impact of mosquito-borne diseases on human populations [25, 26]. Table 1 presents the major mosquito vectors responsible for transmitting diseases in Kerala.

Table 1: Major vectors of mosquito-borne diseases in Kerala

Disease	Vectors
Dengue	*Aedes albopictus*, Ae. *aegypti*
Chikungunya	Ae. *albopictus*, Ae. *aegypti*
Malaria	**Primary vectors:** *Anopheles* culicifacies, An. Fluviatilis, An. *stephensi*, An. dirus, An. minimus **Secondary vectors:** An. annularis, An. philippinensis, An. varuna
Zika	Ae. *albopictus*, Ae. *aegypti*
Japanese Encephalitis	*Culex* tritaeniorhynchus, Cx. Vishnui, Cx. pseudovishnui, Cx. gelidus

Biogeography of Kerala

Kerala, located in the southwestern tip of India, boasts a rich and diverse biogeography influenced by its unique geographical features, climatic conditions, and historical factors [27]. Situated between the Arabian Sea and the Western Ghats Mountain range, Kerala encompasses a variety of ecosystems ranging from coastal plains and wetlands to tropical forests and highland regions [28]. This geographical diversity fosters a wide array of habitats that support diverse flora and fauna [29].

The coastal plains of Kerala are characterized by a network of rivers, estuaries, and backwaters, providing fertile grounds of diverse wetland habitats [30]. Mangrove forests thrive along the coastal areas [31], and serve as crucial breeding grounds for certain species of mosquitoes, particularly those adapted to brackish water environments. Additionally, the presence of paddy fields and other agricultural fields in the coastal plains creates further opportunities for mosquito breeding, especially in areas with poor water management practices [30]. A study on mosquito density carried out in Kerala revealed that the density indices were highest toward the coastal areas [32].

Moving inland, the Western Ghats mountain range significantly influences the biogeography of Kerala. These mountains act as a barrier to the southwest monsoon winds, leading to high rainfall in the windward (western) slopes and relatively drier conditions in the leeward (eastern) slopes [33, 34]. The diverse microclimates and vegetation zones found in the Western Ghats support a rich biodiversity, including numerous mosquito species adapted to specific habitats such as forested areas, stream margins, and high-altitude regions [35]. The presence of human settlements and agricultural activities in the foothills and valleys of the Western Ghats creates additional breeding sites for mosquitoes, contributing to the overall diversity of mosquito species in the region [36].

The state's climate, characterized by high levels of humidity and abundant rainfall during the monsoon season [34], provides favorable conditions for mosquito breeding and population growth. When compared to surveys conducted in June and July, the mosquito diversity indices in May and August were relatively lower. In Kerala, the monsoon season is responsible for the high index values observed in June and July [37]. The warm and humid temperature that prevails for much of the year encourages year-round mosquito activity, which contributes to the transmission of mosquito-borne diseases like malaria, *Dengue* fever, and chikungunya.

Furthermore, Kerala's historical and socio-economic factors also play a role in shaping its biogeography and mosquito diversity. Human activities such as urbanization, deforestation, and land-use changes have led to habitat alterations and fragmentation, influencing mosquito breeding patterns and species distribution [38, 39]. Factors such as population density, sanitation practices, and access to healthcare services can impact the prevalence and transmission of mosquito-borne diseases in different parts of Kerala.

Habitat Preference

Mosquitoes exhibit a complex array of habitat preferences intricately linked to their ecological adaptations. One key aspect of their habitat preference is the selection of breeding sites [40]. Mosquitoes typically deposit their eggs in stagnant or slow-moving water bodies, encompassing natural environments such as ponds, marshes, and swamps, tree holes, leaf axils as well as human-made containers like discarded tires, buckets or even flowerpots [27, 37, 41-45]. The presence of organic matter within these breeding sites, such as decaying vegetation or animal waste, fosters optimal conditions for the development of mosquito larvae.

The breeding behavior of mosquitoes is connected to alterations in natural habitats caused by human activity [46]. Climatic conditions and topographical features also shape the spatial distribution and density of mosquitoes [47]. Factors such as rainfall, humidity, and temperature contribute to increased mosquito populations, while human-induced environmental changes worsen these effects. Specifically, activities resulting in water clogging create additional breeding grounds for mosquitoes, intensifying their prevalence [27].

The selection of breeding sites by female mosquitoes is influenced by various factors, including environmental conditions such as temporal and spatial fluctuations in temperature, water volume and nutrient availability. Both natural and artificial container habitats exhibit significant heterogeneity in these factors [48]. A gravid female mosquito seeks out a water source that is long-lasting and sufficiently nutrient-rich to support the growth, development, and production of pupae, which adult mosquitoes can successfully emerge from. Her choice of a laying site is influenced by a variety of chemical, optical, olfactory, and tactile cues that affect the female's behaviour prior to the egg being laid [49]. Regardless of the species' method for laying eggs, the female may spend several days looking for a suitable spot. Warm, humid weather often encourages insect flight, whereas strong winds discourage mosquitoes from trying to take off. Though mosquitoes fly relatively close to the ground, some gravid females have been photographed hundreds of meters in the air, and nothing is known about these long-range excursions [50]. A wide range of environmental factors influence mosquitoes' choice of oviposition sites, including temperature, precipitation, vegetation, salinity and turbidity of the water, habitat size and amount of sunlight. The temperature of larval habitats affects the development, survival and time of pupation of the larvae as well as their development. Variations in rainfall patterns or seasonal changes can also have an impact on the availability of larval habitats and the productivity of the larvae [51-53].

Mosquito larvae thrive in a wide range of habitats, including natural sites such as tree holes, bamboo stumps and plant pitchers, as well as perennial streams and wetlands. In temperate regions, mosquito species tend to lay their eggs in specific aquatic environments that support distinct plant communities [54]. The presence of mosquito larvae is also affected by habitat size and the presence of predators, which play a crucial role in limiting mosquito populations. The impact of predation varies significantly across different habitat types [10].

Aedes mosquitoes, often referred to as floodwater mosquitoes, flourish in a variety of habitats. Unlike many other mosquitoes, they lay their eggs on moist soil, dry tree holes, and containers rather than directly in standing water [55]. They are prevalent in areas with artificial water stagnation such as waste tire dumps, tanks, bowls, and man-made artificial containers [42]. Ae. *aegypti*, predominantly found in urban settings, displays a distinct preference for human-inhabited areas [56]. Its breeding grounds primarily consist of clean water collections within artificial containers such as tanks and discarded materials commonly found in domestic and peri-domestic environments. A small amount of water is sufficient for their breeding cycle to complete [27]. Contrastingly, Ae. *albopictus* exhibits a broader adaptability, thriving in both urban and rural landscapes [44]. While sharing similar breeding environments with Ae. *aegypti*, including plastic containers, water tanks, coconut shells, and discarded tires, this species demonstrates a wider distribution across various habitats. Notably, it shows remarkable flexibility by breeding in both clean and slightly polluted water, underscoring its adaptive nature [27, 44]. *Aedes vittatus*, on the other hand displays distinct breeding preferences compared to its counterparts. It primarily breeds in rock holes, although it is capable of breeding in a wide range of macro and micro habitats [57]. Its breeding patterns are closely tied to rainfall, with the ability to swiftly complete its life cycle following precipitation events [58]. Mixed breeding of Ae. *aegypti* and Ae. *albopictus* has been observed in habitats such as metal containers, cement tanks, flowerpots, tires, plastic containers, discarded containers, and tree holes. Additionally, the combination of Ae. *albopictus* and Ae. *vittatus* has also been found in cement tanks [43].

Culex mosquitoes, which are vectors for diseases like Japanese encephalitis and West Nile fever, prefer highly polluted habitats such as drains and eutrophic water bodies [59]. They breed in a range of habitats including artificial containers, rock pools, flood pools, irrigation ditches, and stream margins [60]. Cx. *quinquefasciatus* thrives in septic tanks, pit latrines, wells, marshy swamps, cesspits, coir pits, open ponds, and other locations with stagnant, polluted water tainted by human or animal sewage [61]. Their presence in rural, suburban, and urban areas is often associated with human activities that create suitable breeding conditions, such as improper waste disposal and water storage practices. Cx. bitaeniorhynchus are commonly found in abundance along stream margins [60]. In contrast, Cx. vishnui and Cx. tritaeniorhynchus thrive in rural environments, breeding in a diverse range of habitats including stream margins, irrigation ditches, and artificial containers [62]. These species exhibit a preference for ground-water habitats and are known vectors for diseases like Japanese encephalitis and filariasis. Mixed breeding of Ae. *aegypti* and Cx. gelidus has been observed in tires [43].

Anopheles mosquitoes exhibit a preference for habitats characterized by clear to slightly turbid water, commonly found in perennial streams, wetlands, and protected areas with minimal chemical contamination [55, 63, 64]. They demonstrate remarkable adaptability to both ecological and human-induced changes, thriving in diverse environments such as rice fields, streams, ditches, tanks, and other water bodies. Among the species, An. vagus is often found in habitats susceptible to spring tide, where it breeds alongside An. philippinensis in rice fields with algal growth [65, 66]. An. subpictus displays versatility, being observed in various aquatic habitats, with a notable concentration in muddy rain pools and temporary water collections [67]. An. *stephensi*, on the other hand, exhibits a preference for breeding in containers, ranging from battery shells and tin cans to bitumen drums and tires [68]. An. elegans were observed in shaded areas linked to areca nut trees, as the region was abundant with areca nut plantations [69].

Armigeres mosquitoes are commonly found close to human dwellings, particularly in suburban areas with poor sanitation [70]. Its breeding grounds typically comprise polluted water bodies closely linked to human habitation, with favoured habitats including cemented tanks and artificial containers [71]. Cemented tank is one of the breeding habitats for Armigeres subalbatus [72]. Unlike certain other genera, they are less frequently found in natural water bodies.

Mansonia mosquitoes favor habitats characterized by thriving beds of submerged, floating-leaf, or emergent aquatic macrophytes. In contrast to most other mosquito species, the larvae and pupae of *Mansonia* rely on attaching their breathing tubes to the underwater parts of floating aquatic plants, such as roots, stems, or leaves, for survival [73]. *Mansonia annulifera* specifically shows a preference for ponds infested with Pistia stratiotes [74].

Diversity

According to current literature, Kerala has been documented to host a total of 140 mosquito species across 17 genera. The primary vector genera identified include *Anopheles*, *Aedes*, *Culex*, and *Mansonia*, while non-vector genera encompass Armigeres, Heizmannia, Uranotaenia, Orthopodomyia, Haemagogus, Topomyia, Ficalbia, Mimomyia, Tripteroides, Verrallina, Coquilletidia, Toxorhynchites, and Ochlerotatus. Table 2 provides a breakdown of species by genus, revealing 36 species of *Anopheles*, 31 of *Aedes*, 32 of *Culex*, 3 of *Mansonia*, 4 of Armigeres, 4 of Heizmannia, 11 of Uranotaenia, 2 of Orthopodomyia, 4 of Ficalbia, 3 of Mimomyia, 4 of Verrallina, and 1 species each of Haemagogus, Topomyia, Tripteroides, Coquilletidia, Toxorhynchites, and Ochlerotatus identified thus far [27, 36, 41, 42, 55, 70, 75-81].

Table 2: List of mosquito species in Kerala

No.	Genus	Species
1.	*Anopheles*	1) An. culicifacies Giles, 1901 2) An. fluviatilis James, 1902 3) An. *stephensi* Liston, 1901 4) An. dirus Peyton & Harrison, 1979 5) An. pallidus Theobald, 1901 6) An. minimus Theobald, 1901 7) An. aitkenii James, 1903 8) An. insulaeforum (Swell. & Swell.), 1919 9) An. nigerrimus Giles, 1900 10) An. culiciformis Cogill, 1903 11) An. sintoni Puri, 1929 12) An. pseudosundaicus Tyagi *et al.*, 2009 13) An. hyrcanus (Pallas), 1771 14) An. elegans (James), 1903 15) An. tesselatus Theobald, 1901 16) An. majidi Young and Majid, 1928 17) An. subpictus Grassi, 1899 18) An. vagus Doenitz, 1902 19) An. moghulensis Christophers, 1924 20) An. karwari (James), 1902 21) An. jamesi Theobald, 1901 22) An. splendidus Koiduzmi, 1920 23) An. annularis Van der Wulp, 1884 24) An. philippinensis Ludlow, 1902 25) An. aconitus Doenitz, 1902 26) An. jeyporiensis James, 1902 27) An. maculatus Theobald, 1901 28) An. varuna Iyengar, 29) An. barbirostris Van der Wulp, 1884 30) An.peditaeniatus 31) An. sinensis (Wiedemann) 32) An. Jamesii (Theobald, 1901) 33) An. Theobaldi 34) An. (Ano.) gigas (Giles, 1901) 35) An. (Cel.) kochi (Doenitz, 1901) 36) An. (Cel.) tessellatus (Theobald, 1901)
2.	*Aedes*	1) Ae. *aegypti* Linnaeus, 1762 2) Ae. *albopictus* (Skuse), 1894 3) Ae. kanarensis Barraud, 1934

		4) Ae. desmotes Giles, 1904 5) Ae. barraudi (Edwards), 1934 6) Ae. khasani Edwards, 1922 7) Ae. chrysolineatus (Theobald), 1907 8) Ae. mediopunctatus Theobald, 1905 9) Ae. cautus Barraud, 1924 10) Ae. ostentatio (Leicestor), 1908 11) Ae. butleri Theobald, 1901 12) Ae. gubernatoris (Giles), 1901 13) Ae. cogilli Edwards, 1922 14) Ae. Sub*albopictus* Barraud, 1931 15) Ae. vexans (Meigen), 1830 16) Ae. harveyi Barraud, 1923 17) Ae. agastyai Tewari & Hiriyan, 1992 18) Ae. rubenae Tewari & Hiriyan, 1992 19) Ae. menoni Mattingly 1958 20) Ae. caecus (Theobald), 1901 21) Ae. andamanensis Edwards, 1922 22) Ae. *vittatus* (Bigot), 1861 23) Ae. greenii Theobald, 1903 24) Ae. walbusTheobald, 1905 25) Ae. Niveus 26) Ae. pseudotoeniatus 27) Ae. scatophagoides 28) Ae. macdougalli 29) Ae. nov*albopictus* 30) Ae. psuedo*albopictus* 31) Ae. (Aedimorphus) pipersalatus (Giles, 1901)
3.	*Culex*	1) Cx. *quinquefasciatus* 2) Cx. tritaeniorhynchus Giles, 1901 3) Cx. vishnui Theobald, 1901 4) Cx. pseudovishnui Colles, 1957 5) Cx. gelidus Theobald, 1901 6) Cx. modestus Ficalbi, 1890 7) Cx. bitaeniorhynchus Giles, 1901 8) Cx. cornutus Edwards, 1922 9) Cx. epidesmus (Theobald), 1910 10) Cx. brevipalpis (Giles), 1902 11) Cx. uniformis Theobald, 1905 12) Cx. khazani Edwards, 1922 13) Cx. cinctellus Edwards, 1922 14) Cx. mammilifer Leicestor, 1908 15) Cx. sitiens Wiedemann, 1828 16) Cx. uni*vittatus* Theobald, 1901 17) Cx. whitmorei (Giles), 1904 18) Cx. mimeticus Noe, 1899 19) Cx. infantulus Edwards, 1922 20) Cx. minutismus (Theobald), 1907 21) Cx. mimulus Edwards, 1915 22) Cx. infula Theobald, 1901 23) Cx. fuscocephala Theobald, 1907 24) Cx. sinensis Theobald, 1903 25) Cx. malayi Leicester, 1908 26) Cx. mimuloides Barraud, 1924 27) Cx. pallidothorax Theobald, 1905 28) Cx. fuscanus Wiedemann, 1820 29) Cx. Tritaeneorynchus 30) Cx. Lophoceratomya sp. 31) Cx. (Lophoceraomyia) minutissimus (Theobald,1907) 32) Cx. (Lop.) uniformis (Theobald,1905)
4.	*Mansonia*	1) Ma. *annulifera* (Theobald), 1901 2) Ma. uniformis (Theobald), 1901 3) Ma. indiana
5.	Armigeres	1) Ar. subalbatus 2) Ar. flavus (Leicester), 1908 3) Ar. aureolineatus (Leicester), 1908 4) Ar. annulipalpis (Theobald), 1910
6.	Heizmannia	1) Hz. metallica (Leicester), 1908 2) Hz. chandi Edwards, 1922 3) Hz.greeni (Theobald), 1905

		4) Hz.indica (Theobald), 1905
7.	Uranotaenia	1) U. alboannulata (Theobald), 1905 2) U.luteola Barraud, 1934 3) U. atra Theobald, 1905 4) U. hebes Barraud, 1931 5) U. orientalis Barraud, 1926 6) U. testacea Theobald, 1905 7) U. bimaculata Leicestor, 1908 8) U. annandalei Barraud, 1926 9) U. christophersi Barraud, 1926 10) U. maculipleura Leicester, 1908 11) U. stricklandi
8.	Orthopodomyia	1) Or. flavithorax Barraud, 1927 2) Or. anopheloides (Giles), 1903
9.	Ficalbia	1) Fi. minima (Theobald), 1901 2) Fi. (Etorleptiomyia) luzonensis (Ludlow,1905) 3) Fi. (Mimomiya) hybrid a (Leicester,1908) 4) Fi. (Mim.) chamberlaini (Ludlow,1904)
10.	Mimomyia	1) Mi. hybrida (Leicester), 1908 Mi. chamberlaini (Ludlow), 1904 Mi. luzonensis (Ludlow), 1905
11.	Verrallina	1) Ve. uniformis (Theobald), 1910 2) Ve. agrestis (Barraud), 1931 3) Ve. seculata (Menon), 1950 4) Ve. lugubris
12.	Haemagogus	1) He. discrepans Edwards, 1922
13.	Topomyia	1) To. aureoventer (Theobald), 1920
14.	Tripteroides	1) Tp. affinis (Edwards), 1913
15.	Coquilletidia	1) Cq. crassipes van der Wulp, 1892
16.	Toxorhynchites	1) Tx. splendens
17.	Ochlerotatus	1) Oc. Wardi (mosquitoes of the mangrove forest)

Disease and outbreaks in Kerala

Dengue is the most significant arthropod-borne viral disease in terms of public health. While only nine countries reported *Dengue* cases in the 1950s, it is now prevalent in over 100 countries globally [82]. *Dengue* fever, caused by the *Dengue* virus and transmitted primarily by *Aedes* mosquitoes, is a debilitating illness characterized by symptoms such as high fever, eye pain, nausea, vomiting, severe joint and muscle pain, headache, and a characteristic skin rash [83]. Ae. *aegypti* is the primary vector responsible for transmitting approximately two-thirds of *Dengue* cases worldwide [84]. While most cases of *Dengue* fever resolve on their own with supportive care, a small percentage of patients progress to severe forms of the disease, including *Dengue* hemorrhagic fever (DHF) and *Dengue* shock syndrome (DSS). *Dengue* Haemorrhagic Fever (DHF), a severe complication of *Dengue*, is characterized by bleeding tendencies, low platelet count, and plasma leakage. *Dengue* Shock Syndrome (DSS) encompasses all DHF symptoms, along with circulatory failure, age-specific low blood pressure, and low pulse pressure. Although DHF and DSS can be fatal, patients can fully recover without any long-term effects if diagnosed early and treated properly [85-87]. The initial outbreak of *Dengue* was documented in Kerala in 1997, marking the onset of a rapid escalation in the annual incidence of *Dengue* virus cases thereafter [88]. Presently, *Dengue* stands out as the most perilous mosquito-transmitted illness within the state, both in terms of case count and fatalities. This holds true not only locally but also on a global scale. Over the past six decades, *Dengue* has proliferated across tropical regions, impacting more than half of the world's inhabitants. The anticipated expansion of *Dengue*'s geographical reach is attributed to climate shifts, urban development, and the infiltration of vectors into novel territories [89]. In Kerala, the main vector of the *Dengue* virus is Ae. *albopictus* [90].

Chikungunya, also transmitted by *Aedes* mosquitoes, shares some clinical similarities with *Dengue* fever, including fever, joint pain, headache, muscle pain, and rash [91]. However, chikungunya is distinguished by prominent joint pain, which can be severe and persist for months or even years in some cases [92]. While chikungunya is rarely fatal, it can significantly impact quality of life due to the prolonged joint pain experienced by some patients [93]. The earliest outbreak of chikungunya in Kerala transpired in 2006, impacting 14 districts. The resurgence of the disease took place in the Kozhikode district in May 2009 [94].

Malaria is an illness caused by protozoan parasites belonging to the genus Plasmodium and transmitted through the bites of infected *Anopheles* mosquitoes, is a potentially life-threatening disease that affects millions of people worldwide, particularly in tropical and subtropical regions [95]. The symptoms of malaria typically include fever, shivering, cough, respiratory distress, headache, muscle aches, and fatigue, and they can vary depending on the species of Plasmodium involved. If left untreated, malaria can progress to severe complications, such as cerebral malaria (a severe form of the disease affecting the brain), severe anemia, and organ failure, which can be fatal, especially in young children and pregnant women [96, 97]. Malaria has had a historical presence in Kerala, dating back to ancient times. While efforts led to its eradication as early as 1965, cases of imported malaria persisted thereafter. Furthermore, indigenous malaria began to show signs of resurgence starting from 1969 [98]. In Kerala, malaria is caused by two species of Plasmodium: Plasmodium vivax and Plasmodium falciparum. Malaria parasites have been identified in An. culicifacies, An. fluviatilis, An. jeyporiensis, and An. varuna, in Kerala [90].

West Nile fever, caused by the West Nile virus and transmitted by infected *Culex* mosquitoes, often presents with mild, flu-like symptoms, including fever, headache, body aches, sore throat, conjunctivitis, retrobulbar pain, maculopapular or roseolar rash, myalgia, arthralgia, anorexia, nausea, abdominal pain, diarrhea, and fatigue [99, 100]. However, in a small percentage of cases, typically among older adults or individuals with weakened immune systems, West Nile fever can lead to more severe neurological complications, such as encephalitis (inflammation of the brain) or meningitis (inflammation of the membranes surrounding the brain and spinal cord). These neurological complications can result in long-term disability or death [101]. The initial occurrence of West Nile fever in the state was documented in 2011. Subsequently, the virus was identified in the years 2018, 2019, 2021, and 2022 [102]. Up to this point in the year, the state has reported at least 10 confirmed cases of West Nile virus, along with two deaths that are currently under suspicion.

Japanese encephalitis, caused by the Japanese encephalitis virus and primarily transmitted by *Culex* mosquitoes in rural and agricultural areas, is a serious viral infection that affects the brain [103, 104]. The symptoms of Japanese encephalitis typically include fever, headache, nausea, convulsions, respiratory difficulties, disorientation, coma, seizures, and paralysis [105, 106]. While the majority of individuals infected with Japanese encephalitis virus may remain asymptomatic, a small percentage of cases can develop severe neurological complications, leading to permanent brain damage or death, particularly among children [104, 107]. The first outbreak of Japanese encephalitis in Kerala took place in the Kuttanad region during January and February of 1996, resulting in 105 cases and 31 fatalities [108]. In Kerala, the Japanese Encephalitis virus has been detected in Cx. tritaeniorhynchus, Cx. gelidus, Ma. uniformis, Ma. indiana, Ma. *annulifera*, and An. subpictus. The primary vectors of Japanese Encephalitis in Kerala are Cx. tritaeniorhynchus and Ma. indiana [90].

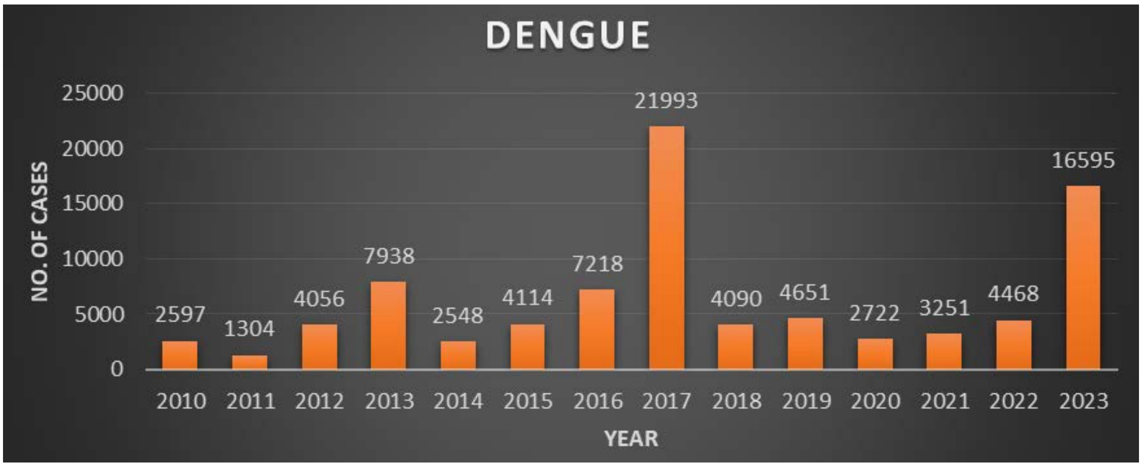
Zika virus, also transmitted primarily by *Aedes* mosquitoes, gained global attention due to its association with severe birth defects, including microcephaly, in infants born to mothers infected during pregnancy [109, 110]. In addition to fever, rash, joint pain, and conjunctivitis (red eyes), Zika virus infection can cause Guillain-Barré syndrome, a rare neurological disorder that can lead to muscle weakness and paralysis [111-113]. While most cases of Zika virus infection are mild and self-limiting, the potential for severe birth defects and neurological complications particularly among pregnant women has prompted significant public health concern and efforts to prevent its transmission [114]. The initial case of Zika was recorded in Thiruvananthapuram, in 2021, initiating a subsequent outbreak comprising 90 cases [113, 115]. Zika incidences were subsequently reported in the state in 2022 and 2023, with 15 and 13 cases respectively. Thus far, there are no suspected Zika-related fatalities.

Table 3 and graphs 1-6 presents data on the number of cases and deaths from Chikungunya, *Dengue*, Japanese Encephalitis, Malaria, West Nile virus and Zika virus spanning the years 2010 to 2023 in Kerala.

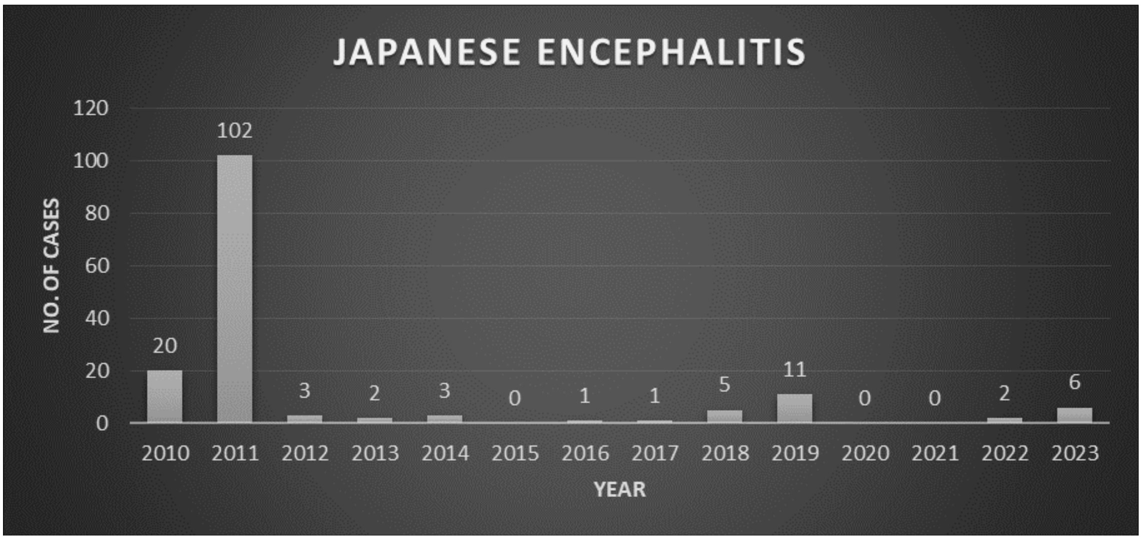
Table 3: Number of cases and deaths due to mosquito-borne diseases in Kerala 2010-23

Year	Chikungunya		*Dengue*		Japanese encephalitis		Malaria		West nile virus		Zika virus	
	Cases	Death	Cases	Death	Cases	Death	Cases	Death	Cases	Death	Cases	Death
2010	210	0	2597	17	20	5	2299	7	0	0	0	0
2011	81	0	1304	10	102	8	1993	2	33	0	0	0
2012	62	0	4056	16	3	1	2036	3	0	0	0	0
2013	247	0	7938	29	2	0	1634	0	0	0	0	0
2014	264	0	2548	13	3	2	1751	6	0	0	0	0
2015	152	0	4114	29	0	0	1549	4	0	0	0	0
2016	124	0	7218	21	1	0	1540	3	0	0	0	0
2017	54	0	21993	165	1	0	1194	2	0	0	0	0
2018	76	0	4090	32	5	2	908	0	1	0	0	0
2019	109	0	4651	14	11	2	656	1	11	2	0	0
2020	558	0	2722	22	0	0	268	1	0	0	0	0
2021	334	0	3251	27	0	0	309	1	1	0	90	0
2022	66	0	4468	58	2	0	439	0	3	1	15	0
2023	31	0	16595	55	6	1	551	7	0	0	13	0

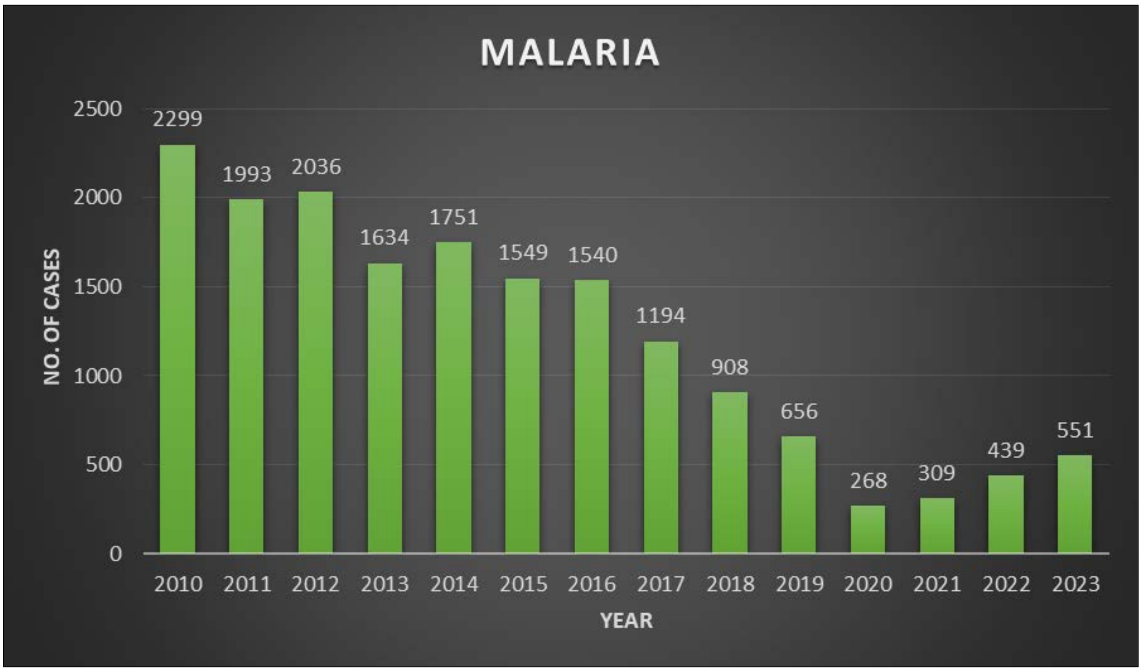
Graph 1: Chikungunya cases from 2010-23



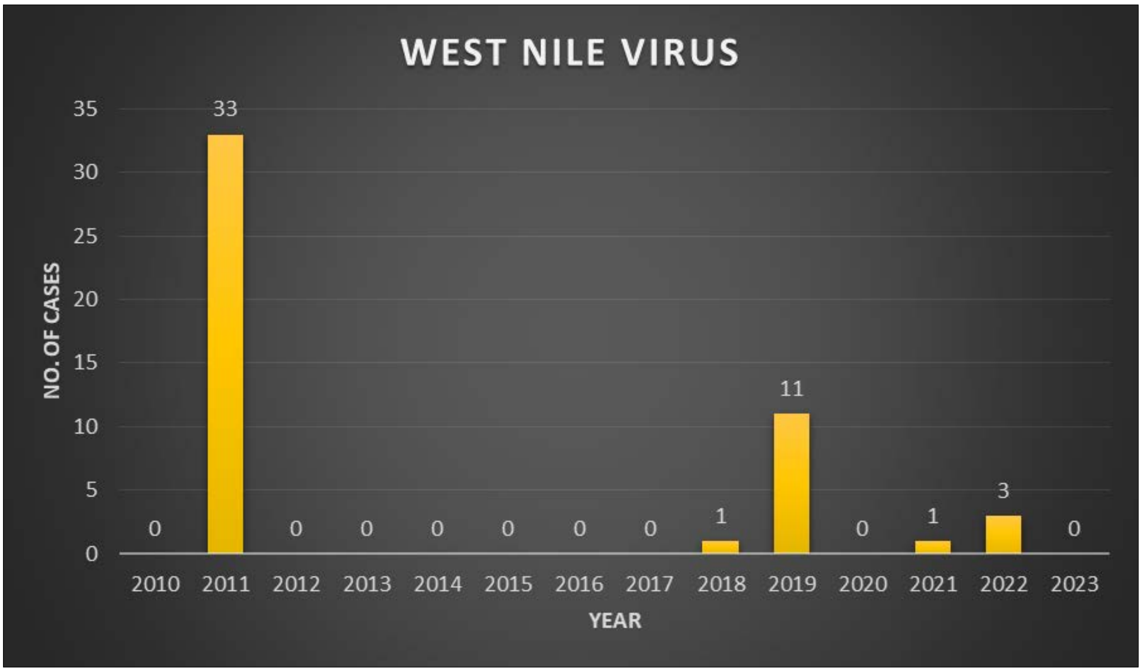
Graph 2: *Dengue* cases from 2010-23



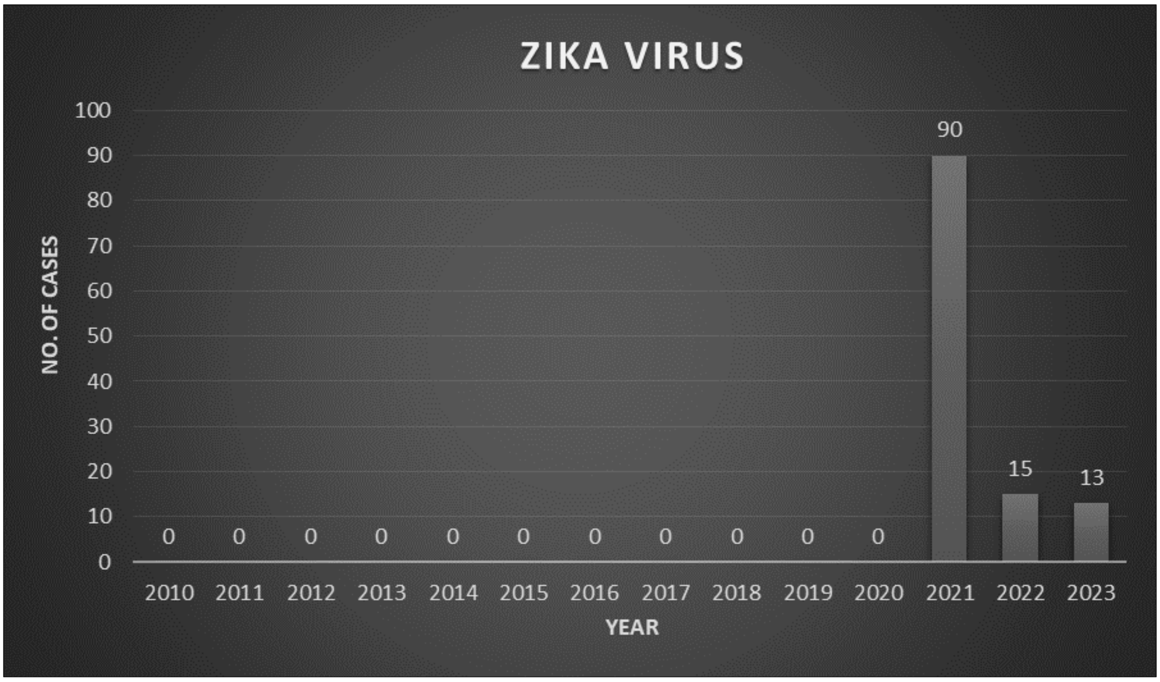
Graph 3: Japanese Encephalitis cases from 2010-23



Graph 4: Malaria cases from 2010-23



Graph 5: West Nile Virus cases from 2010-23



Graph 6: Zika Virus cases from 2010-23

Control

Mosquito control includes a wide range of strategies aimed at reducing mosquito populations and minimizing the transmission of mosquito-borne diseases. These strategies typically involve integrated approaches that target larval habitats, adult mosquitoes, and disease transmission pathways [25]. One key component of mosquito control is habitat management, which focuses on eliminating or modifying mosquito breeding sites to reduce larval populations. This may involve removing standing water from containers, clearing vegetation from water bodies, and improving drainage systems to prevent the accumulation of stagnant water [3]. Additionally, larvicides and biological control agents, such as bacteria or fish (Toxorhynchites), that feed on mosquito larvae, may be deployed to target mosquito breeding sites in aquatic habitats [116]. In certain countries, the bio-insecticides Bacillus thuringiensis israeliensis and Bacillus sphaericus are utilized for effective control, offering an environment friendly solution [26].

In addition to targeting mosquito larvae, adult mosquito populations may also be controlled using insecticides through space spraying or targeted application to resting sites [116]. These insecticides are applied using various methods, including fogging machines, sprayers, or larviciding treatments [25]. However, insecticide resistance among mosquito populations is a growing concern, highlighting the need for integrated approaches that combine chemical control with other strategies, such as mosquito surveillance and community engagement [117]. The activities comprise formation of community committees, implementing vector control measures, and conducting source reduction efforts with community involvement and inter-sectoral coordination [118]. Furthermore, community engagement and public awareness campaigns play crucial roles in mosquito control efforts, empowering individuals to take proactive measures to reduce mosquito breeding sites in their surroundings and protect themselves from mosquito bites through the use of repellents and protective clothing. Most rural households and all urban households reported using at least one personal measure against mosquitoes. In rural areas, fumigation is the preferred method, while urban households commonly use liquid vaporizers [119]. By combining these diverse approaches into integrated mosquito control programs tailored to local ecological and epidemiological contexts, public health authorities can effectively reduce mosquito populations, mitigate the transmission of mosquito-borne diseases, and protect human populations from the burden of these illnesses.

Conclusion

This review highlights the intricate relationship between mosquito diversity, environmental factors, and the transmission dynamics of mosquito-borne diseases in Kerala. The diverse array of mosquito species, including *Aedes*, *Anopheles*, and *Culex* genera, reflects Kerala's varied ecosystems and climatic conditions, posing significant challenges for disease control efforts. Endemic mosquito-borne diseases such as *Dengue*, malaria, chikungunya, and Japanese encephalitis continue to afflict the region, with seasonal outbreaks intensified by factors like monsoon rainfall. Integrated vector management strategies, including larval source reduction, insecticide spraying, and community mobilization, are essential for mitigating disease transmission. Collaborative efforts among researchers, policymakers, and public health authorities are crucial for implementing sustainable interventions and safeguarding the health of Kerala's population.

Understanding mosquito diversity and its implications for disease transmission is paramount for effective disease control in Kerala. By combining scientific knowledge with evidence-based interventions, we can address the complex challenges posed by mosquito-borne diseases and strive towards long-term health outcomes for Kerala's communities.

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