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REVIEW

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Vector-borne diseases on Borneo island: a scoping review

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Abstract

Background Borneo, the third largest island in the world, is facing a significant burden of emerging and re-emerging vector-borne diseases due to rapid changes in primary tropical rainforests and urban landscapes. These vector-borne diseases include the endemic epidemic cycles that occur in the more populated and urbanized areas, as well as the possible transmission through enzootic and sylvatic transmission cycles that occur mainly in the overlapping landscapes or among the indigenous population in the forest. The island will be changed significantly in the future due to the increase in human activities, especially mega events such as the relocation of the Indonesian capital to Nusantara in East Kalimantan Borneo, increasing urbanization, agriculture, hydropower projects, ecotourism activities in Sabah, North Borneo, and Sarawak, Central and South Borneo. Therefore, an overview of the current situation of vector-borne diseases is crucial for the next possible epidemic preparedness.

Methods This study conducted the PRISMA-ScR scoping review and formulated a set of research questions to identify current trends in vector-borne diseases in Borneo. These questions aim to identify which diseases have been studied, what geographical areas have been covered by the research, how the One Health approach—encompassing human, animal and environmental factors—is integrated, and what gaps and challenges exist in addressing these diseases.

Results A total of 2241 references were screened for eligibility and 117 articles were selected for review. The majority of the materials focused on mosquitoes and malaria, and the One Health elements focused mainly on humans.

Conclusions This review has identified the most and least studied vector-borne diseases and highlighted some of the gaps in knowledge and research on vector-borne diseases on the island of Borneo. Future studies should particularly focus on other neglected diseases such as Zika, chikungunya, Japanese encephalitis, filariasis and tick-borne diseases. In addition, advanced surveillance systems will be developed to improve early detection and response specifically for remote regions where vector-borne diseases are endemic or emerging.

Keywords Sabah, Sarawak, Brunei, Kalimantan, Zoonotic diseases, Mosquito-borne diseases, One health

Background

Borneo is an island in Southeast Asia shared by Indonesia (Kalimantan), Malaysia (Sabah and Sarawak) and Brunei. This third largest island in the world has a large area of primary tropical rainforest, a great diversity of flora and fauna, indigenous peoples, different climatic zones due to the different altitudes [1]. However, increasing human activities such as deforestation for urban development, land alteration through agricultural activities, logging and poaching, and intensive ecotourism

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are impacting ecosystems where endemic, epidemic and enzootic cycles of vector-borne diseases exist [2, 3]. In particular, the crossing of borders of forests or rural areas by humans can lead to a spillover of enzootic transmission from natural hosts to humans and cause zoonotic and sylvatic transmission [4]. Recent outbreaks of vector-borne diseases such as Zika [5] and the emergence of zoonotic malaria [6] show how difficult it is to control this infectious disease with current practices in Borneo. According to a report by the World Health Organization (WHO), only one part of the island of Borneo, Kalimantan, already has the second highest number of malaria cases in Asia and the Pacific after India [7]. For example, in 2018, Jeffree et al. [8] reported two indigenous cases of ZIKV infection from the residential area of Kota Kinabalu, Sabah, North Borneo, indicating spillover from the forest area to the urban area; Ali et al. [9] reported ZIKA-positive cases in both *Aedes albopictus* vectors and humans from Miri Sarawak, a mixed suburban and forest area. Additionally, Lempang et al. [10] investigated and reported the emerging and increasing cases of primate malaria in Kalimantan Indonesia, which poses great challenges to the region in controlling malaria cases. Although the governments of the three countries have set a target to eliminate malaria by 2030, the number of cases has remained relatively stable, and the emergence of zoonotic malaria has further complicated the situation. In addition, other vector-borne diseases caused by sandflies, ticks, fleas and lice have generally been relatively neglected, despite being labelled by the WHO as the most prevalent vector-borne diseases in the world [11, 12].

The threat from zoonotic pathogens and emerging infections is clear. These threats are exacerbated and accelerated by the increasing impact of various factors, such as environmental change and habitat loss due to human activities (see Fig. 1). Some of the major human activities in the Bornean rainforest include deforestation due to the relocation of the Indonesian capital, urbanization, hydropower development and the intensification of ecotourism in the two Malaysian states of Sabah and Sarawak. These activities subsequently affect the rainforest ecosystem, especially the health of the animals whose habitat is likely to change. It is, therefore, time to recognize the interconnectedness between humans, animals, and the environment, especially in the transmission and spread of vector-borne diseases. The One Health approach recognizes that human, animal, and environmental health are interconnected and emphasizes the need for collaboration between different sectors to address public health challenges [13]. Such approaches use integrated, interdisciplinary methods that recognize the interrelationships between humans, animals (including wildlife, livestock, aquatic organisms, and domestic animals) and environmental factors (including the natural and built environment and climate change), with the aim of improving outcomes for human, animal, and ecosystem health.

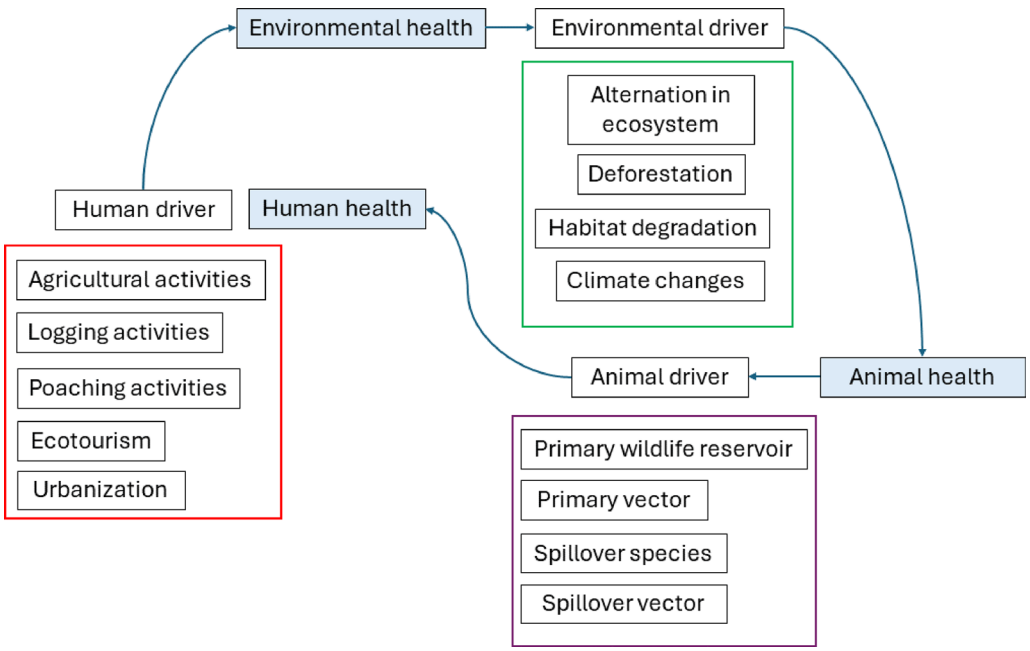

Fig. 1 Illustration of the impact of human activities on the environment and animal health according to the One Health paradigm

The aim of this review was to examine the literature on vector-borne disease studies on the island of Borneo, particularly in recent years when zoonotic and sylvatic transmission has increased significantly, and to identify the gaps in knowledge and research. The aim of this study is to summarize the materials in a table for future documentation, to illustrate the geographical area covered or less covered, to analyse the research topic of the literature in Borneo based on the One Health concept and finally to highlight some gaps and challenges in disease management in Borneo.

Methods

This scoping review was conducted in accordance with the PRISMA-ScR guidelines [14], which contain 22 checklist items. Most of the items were adopted in this study, namely rationale, objectives, eligibility criteria, search strategies, selection of evidence sources, data collection, results and discussion. In this study, a series of research questions were formulated to identify current trends in vector-borne diseases in Borneo. These questions aim to identify which diseases have been researched, which geographical areas are covered by research, how the One Health approach—encompassing human, animal and environmental factors—is integrated, and what gaps and challenges exist in addressing these diseases. To answer these questions, this study established eligibility criteria for the selection of relevant studies. The inclusion criteria focused on original research such as surveillance studies and epidemiological studies on vector-borne diseases in Borneo published in peer-reviewed journals and in English, Malay and Indonesian within the last five years. This study focused on studies dealing with diseases such as malaria, dengue, Zika and chikungunya as well as vectors such as mosquitoes, ticks, lice and sandflies. Exclusion criteria were opinion articles, non-peer-reviewed papers, systematic reviews and studies that did not focus on Borneo or did not address relevant vector-borne diseases.

In this study, a keyword and Boolean logic search strategy was used, applying bibliometric methods and searching the databases with Boolean logic for the keyword "vector-borne diseases" according to the WHO [11], namely "malaria", "dengue", "Zika" and three emerging diseases—"chikungunya", "lymphatic filariasis" and "Japanese encephalitis". In addition, the vector is also used as a keyword in this study, i.e. "mosquito", "tick", "sand fly", "lice" or "flea". The keywords used for the query were based on the WHO [5, 11] and the epidemics/early epidemics reported by the health authorities in Borneo, Malaysia, Brunei and Indonesia, i.e. "mosquito", "tick", "lice", "flea", "sand fly", which are vectors, and "malaria", "dengue", "Zika", "chikungunya", "Japanese encephalitis", "lymphatic filariasis". The query was combined with the Boolean operation AND/OR, with the scope of "Borneo" and ">2017". The abstracts and titles of the articles were independently assessed by each author of the respective article. If the abstract, title, or both related to the study of vector-borne diseases in Borneo, they were considered for further reading; otherwise, they were filtered out. Following this procedure, an article was selected only if all the authors agreed on its relevance to vector-borne diseases in Borneo. In the next step, the articles addressing the three components of the One Health approach were considered, and the topic was assigned to the corresponding article. Due to the focus on *Plasmodium knowlesi* as the causative agent of zoonotic malaria, most of the literature was heavily focused on this pathogen and did not fully fulfil the criteria of this study. In this study, materials related to the research questions were selected. Some of them, mainly related to genetic analysis, e.g. *P. knowlesi* genetic diversity analysis [15, 16], and modelling, e.g. serological assessment of risk factors for malaria exposure [17, 18], have been moved to Appendix 1 (Genetic and modelling perspective for *P. knowlesi*-related materials).

The selection criteria for the research articles were set to include papers published between 2017 and 2023. The selection of the initial year 2017 is due to the duration suitable to capture mega events on the island of Borneo, such as the control of human movements during the COVID pandemic [19], the reopening of ecotourism, the construction of a hydropower plant and the relocation of the capital of Indonesia. These events contributed to two main causes that were considered: the emergence of zoonotic malaria and the increase in human activities in the forest region, such as urbanization and deforestation in the states of Sabah and Sarawak in Malaysia and the relocation of the capital from Indonesia to Kalimantan Borneo. The scientific databases Google Scholar, PubMed and Scopus were searched to compile a comprehensive bibliography of research papers on vector-borne diseases in Borneo literature. The selection of databases was based on three main arguments: (1) the peer-review process of the articles to be included in the database, which ensures the quality and reliability of the selected articles. (2) PubMed was the main database for most publications on infectious diseases, including vector-borne diseases. (3) The Google search engine was able to capture some of the important literature published in non-indexed databases.

Results

Figure 2 shows the number of studies selected on the basis of the methods described in Sect. 2. To account for the highly neglected vector-borne diseases, 62

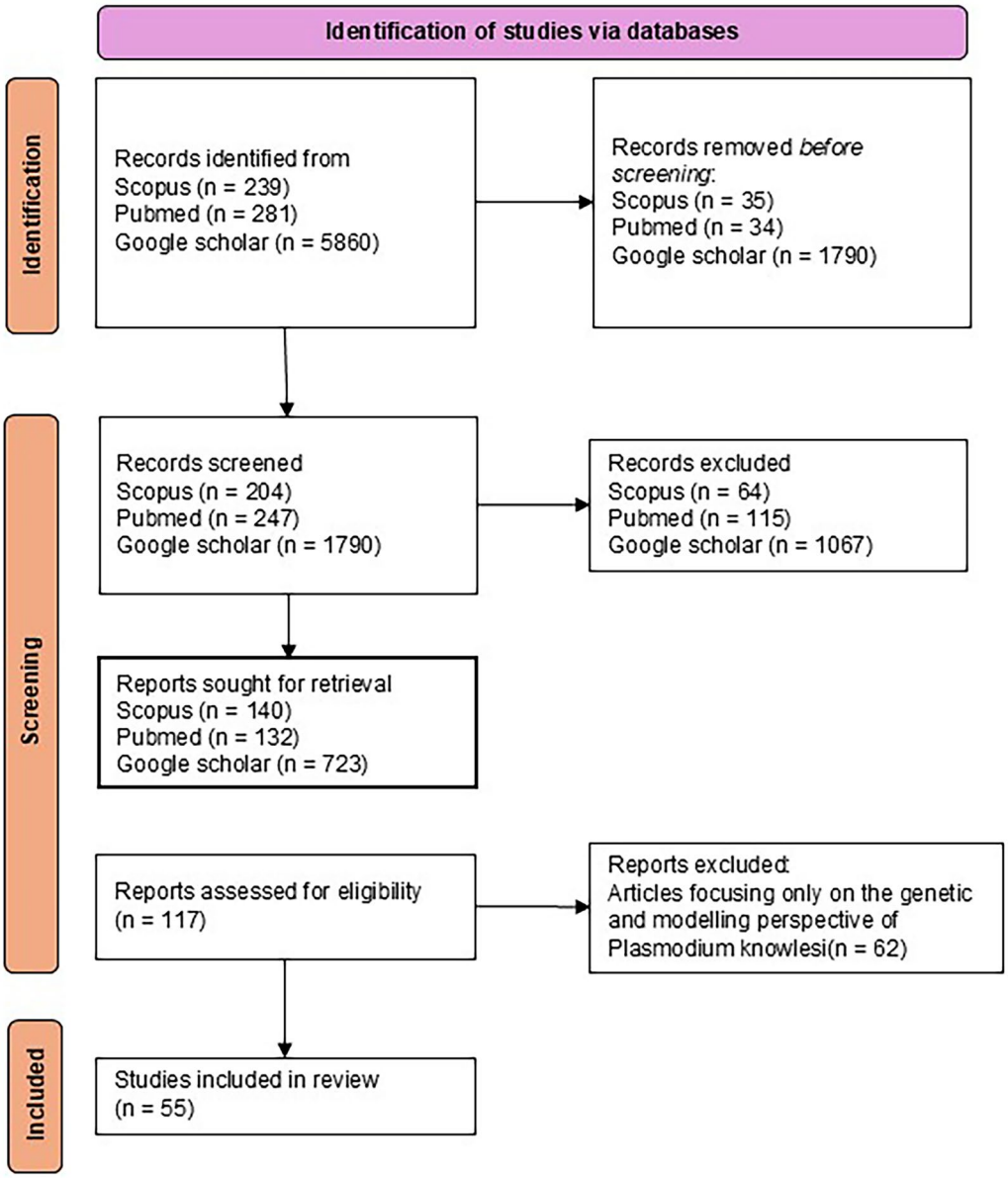

Fig. 2 Results of the relevant articles after the selection procedure

studies dealing only with *P. knowlesi* and mainly addressing genetic and modelling aspects, e.g. investigations of *Plasmodium* cytoplasm or receptors and interaction with the host, epidemiological modelling, were separated as a second curated document as Appendix 1. Nevertheless, these 62 studies were analysed together and presented in the following section. A further 55 articles were summarized in this study that answered three of the research questions, including the link to the One Health approach, which are summarized in Table 1. The table also lists the literature with the respective vector, species, pathogen, diseases, study location (e.g. where the vector or pathogen sample was obtained) and the element of the One Health approach.

Vector-borne diseases in Borneo

As far as the vector is concerned, the mosquito was the most frequently investigated, namely in 86% of the available literature (Fig. 3). Among the mosquito-borne diseases, malaria was the most frequently studied disease, accounting for 72% of the total literature on vector-borne diseases found in this study (Fig. 4).

Table 1 Summary of the literature review on vector-borne diseases based on the species of vector, pathogen and location Borneo and the components of the One Health approach

References	Year	Location	Vector	Species	Pathogen	Diseases	One Health
Naserrudin et al. [61]	2023	Sabah	Mosquito	*NA*	*NA*	Malaria	Human
Turkiewicz et al. [64]	2023	Sabah	Mosquito	*NA*	*P. knowlesi*	Malaria	Human
Ahmed et al. [57]	2023	Sarawak	Mosquito	*NA*	*P. knowlesi*	Malaria	Human
Pramasivan et al. [63]	2023	Sarawak	Mosquito	*An. balabacensis* *An. cracens* *An.introlatus* *An. latens*	*P. knowlesi*	Malaria	Vector
Lau et al. [74]	2023	Sarawak	Tick	*Ixodes granulatus* *Haemaphysalis hystricis, Haemaphysalis shimoga, Dermacentor compactus, Dermacentor steini and Dermacentor atrosignatus*	*Rickettsia heilongjiangensis* *Ehrlichia sp.* *Anaplasma sp.* *Bartonella spp.*	Tick-borne	Animal (rodent)
Kazim et al. [80]	2023	Sabah	Louse	*Ischnocera* *Amblycera* *Rhynchophthirina*	*NA*	*NA*	Animal (domestic and wild animal)
Kazim et al. [81]	2022	Sabah	Louse	*Anoplura*	*NA*	*NA*	Animal (domestic and wild animal)
Lau et al. [75]	2022	Sarawak	Tick	*Haemaphysalis shimoga*	*Babesia spp*	*NA*	Animal (rodent)
Chua et al. [77]	2022	Sabah	Mosquito	*An.balabacensis*	*NA*	Malaria	Vector
Sugiarto et al. [7]	2022	Kalimantan	Mosquito	*NA*	*NA*	Malaria	
Sugiarto et al. [37]	2022	Kalimantan	Mosquito	*NA*	*P. vivax* *P. ovale* *P. malariae*	Malaria	Human
Payus and Sentian [62]	2022	Sabah	Mosquito	*NA*	*NA*	Malaria	Environment
Dian et al. [60]	2022	Sabah, Sarawak	Mosquito	*NA*	*NA*	Malaria	Animal (primate)
Gregory et al. [3]	2022	Sabah	Mosquito	*Ae. albopictus*	*NA*	*NA*	Environment/vector
Lau et al. [22]	2022	Sarawak	Mosquito	*Ae. albopictus*	*NA*	Dengue	Vector
Fornace et al. [52]	2022	Sabah	Mosquito	*NA*	*NA*	*NA*	Human/ environment
Chan et al. [86]	2022	Sabah	Mosquito	*NA*	*NA*	lymphatic filariasis and toxoplasmosis	Human
Nada-Raja et al. [88]	2022	Sabah	Mosquito	*NA*	*NA*	Malaria	Animal (monkey)
Isnadi et al. [89]	2022	Sabah	Mosquito	*NA*	*NA*	Malaria	Animal (monkey)
Messina et al. [90]	2022	Sabah	Mosquito	*NA*	*NA*	Malaria	Animal (bird)
Sasmono et al. [83]	2021	Kalimantan	Mosquito	*NA*	dengue	dengue	Human
Kaur et al. [84]	2020	Sabah	Mosquito	*NA*	dengue	dengue	Human
Lau et al. [76]	2020	Sarawak	Tick	*Ixodes granulatus*	*Borrelia miyamotoi* *B. yangtzensis*	Lyme disease	Animal (rodent)
Brown et al. [58]	2020	Sabah	Mosquito	*An. balabacensis*	*NA*	*NA*	Animal (primate)
Jeyaprakasam et al. [65]	2020	Southeast Asia	Mosquito	*NA*	*NA*	*NA*	Human
Ang et al. [13]	2020	Sarawak	Mosquito	*An. Balabacensis* *An. donaldi*	*P. inui* *P. fieldi* *P. cynomolgi* *P. knowlesi*	*NA*	Vector
Brown et al. [30]	2020	Sabah	Mosquito	*An. Balabacensis*	*P. knowlesi*	*NA*	Environment

Table 1 (continued)

References	Year	Location	Vector	Species	Pathogen	Diseases	One Health
Murphy et al. [66]	2020	Sabah	Mosquito	*Ae. aegypti* *Ae. albopictus* *Culex*	*NA*	*NA*	Human
Supriyono and Tan [67]	2020	Sarawak, Kalimatan	Mosquito	*Mansonia annulifera* *Aedes albopictus* *Culex tritaeniorhynchus*	*Brugia malayi*	Lymphatic filariasis	Vector
Kamaruddin et al. [78]	2020	Sarawak	Tick and louse flea	*Haemaphysalis sp.* *Haemaphysalis sp.* *Felicola subrostratus* *Ctenocephalides felis* *Ctenocephalides felis orientis* *Lynxacarus radovskyi* *Otodectes cynotis*	*NA*	*NA*	Animal (cat)
Sasmono et al. [85]	2019	Kalimantan	Mosquito	*NA*	dengue	dengue	Human
Stark et al. [87]	2019	Sabah	Mosquito	*NA*	*NA*	Malaria	Animal (monkey)
Davidson et al. [59]	2019	Sabah	Mosquito	*NA*	*NA*	*NA*	Environment/vector
Fornace et al. [68]	2019	Sabah	Mosquito	*NA*	*NA*	*NA*	Environment
Sato et al. [69]	2019	Sabah	Mosquito	*NA*	*NA*	*NA*	Human
Husnina et al. [70]	2019	Kalimantan	Mosquito	*NA*	*NA*	Dengue	Environment
Mao et al. [79]	2019	Sabah	Tick	*Amblyomma helvolum*	*NA*	*NA*	Animal (snake)
Brown et al. [71]	2018	Sabah	Mosquito	*NA*	*NA*	*NA*	Environment/vector
Chua et al. [72]	2017	Sabah	Mosquito	*An. balabacensis*	Simian *Plasmodium spp.*		Vector
Young et al. [73]	2017	Sarawak	Mosquito	*Aedes* *Anopheles* *Armigeres* *Culex* *Lutxia*	Dengue virus	Dengue	Environment
Ng et al. [20]	2017	Sarawak	Tick and louse	*Ixodes granulatus*, *Haemaphysalis sp.* *Hoplopleura sp*	*NA*	*NA*	Animal (rodent)
Feilen et al. [24]	2017	Kalimantan	Sandfies	*NA*	*NA*	*NA*	Animal (proboscis monkey)
Hastriter et al. [82]	2017	Sarawak	Flea	*Lagaropsylla turba Smit*	*NA*	*NA*	Animal (earwig)

i.e. the topic was not mentioned or studied or analysed in the articles

NA not available

7% of tick-borne diseases and 6% of louse-borne diseases were covered by species and pathogen screening studies, which are crucial for establishing baseline information for future surveillance. In most of these studies, samples were collected from rodents [20–23], which are highly anthropophilic and often act as animal hosts that transmit diseases to humans. There are two studies on these ectoparasites in the literature on fleas, but none of them investigated the possible causative agent.

There is only one study on sandflies in Borneo that relates to the nesting and sleeping habits of proboscis monkey [24]. This may be because relatively little has been reported on sand fly borne diseases, such as leishmaniasis in Borneo. The most comprehensive study on Borneo was published in 1961 by Laurence and Fairchild [25], although there are more recent studies on sand flies and pathogen surveillance in neighboring countries, such as Peninsular Malaysia [26], Thailand [27] and the Philippines [28].

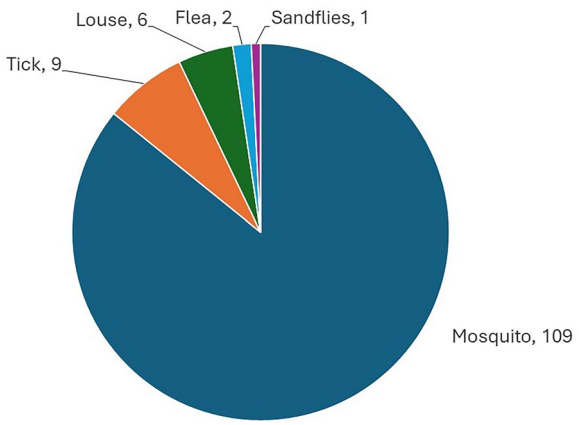

Fig. 3 The composition of the literature depends on the type of vector. The chart has been labelled with the type of vector, followed by the number of literatures

Coverage area in Borneo

To summarize the study sites of reviewed articles, the first author created a visualization, shown in Fig. 5, which aims to describe the region of studies covered by the literature reviewed in this study. Most of the studies reviewed in this study focused on urban and suburban areas. Some of them conducted experiments to compare the biodiversity of vectors in different landscapes and then covered some protected forests [29]. Few of these studies investigated human exposure to zoonotic malaria vectors in Sabah, Malaysian Borneo [30], or rodent and tree shrew ectoparasite fauna in different habitats of Sarawak [31].

Figure 5 also shows the distribution of literature focusing on the island of Borneo. Notably, many of the studies focused on similar areas due to reported cases or existing endemic transmission. This could be because there are many remote areas where it is difficult to collect data, although efforts are ongoing. Several major cities were mentioned in this study, such as the new capital of Indonesia, Nusantara, Kuching Sarawak and Kota Kinabalu Sabah. Figure 5 shows the areas covered by the research areas of the analysed articles.

One Health approach

The One Health approach was not new in the fight against vector-borne diseases, but by emphasizing human well-being, many other factors were severely neglected. This approach was reintroduced after several zoonotic outbreaks, such as those involving Zika and COVID-19 [13, 32], and has drawn the attention of researchers and practitioners to the balance of the three elements of the One Health approach.

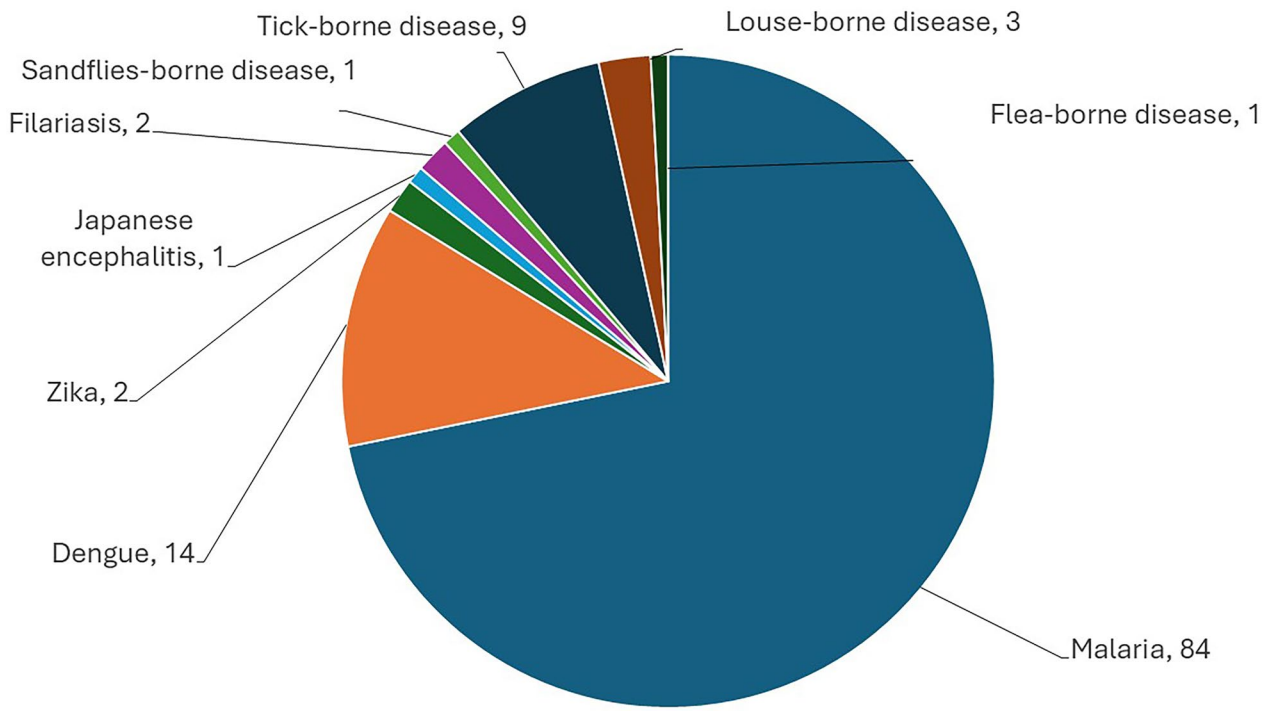

Fig. 4 The composition of the literature is based on diseases. The chart has been labelled with the type of disease, followed by the number of literatures

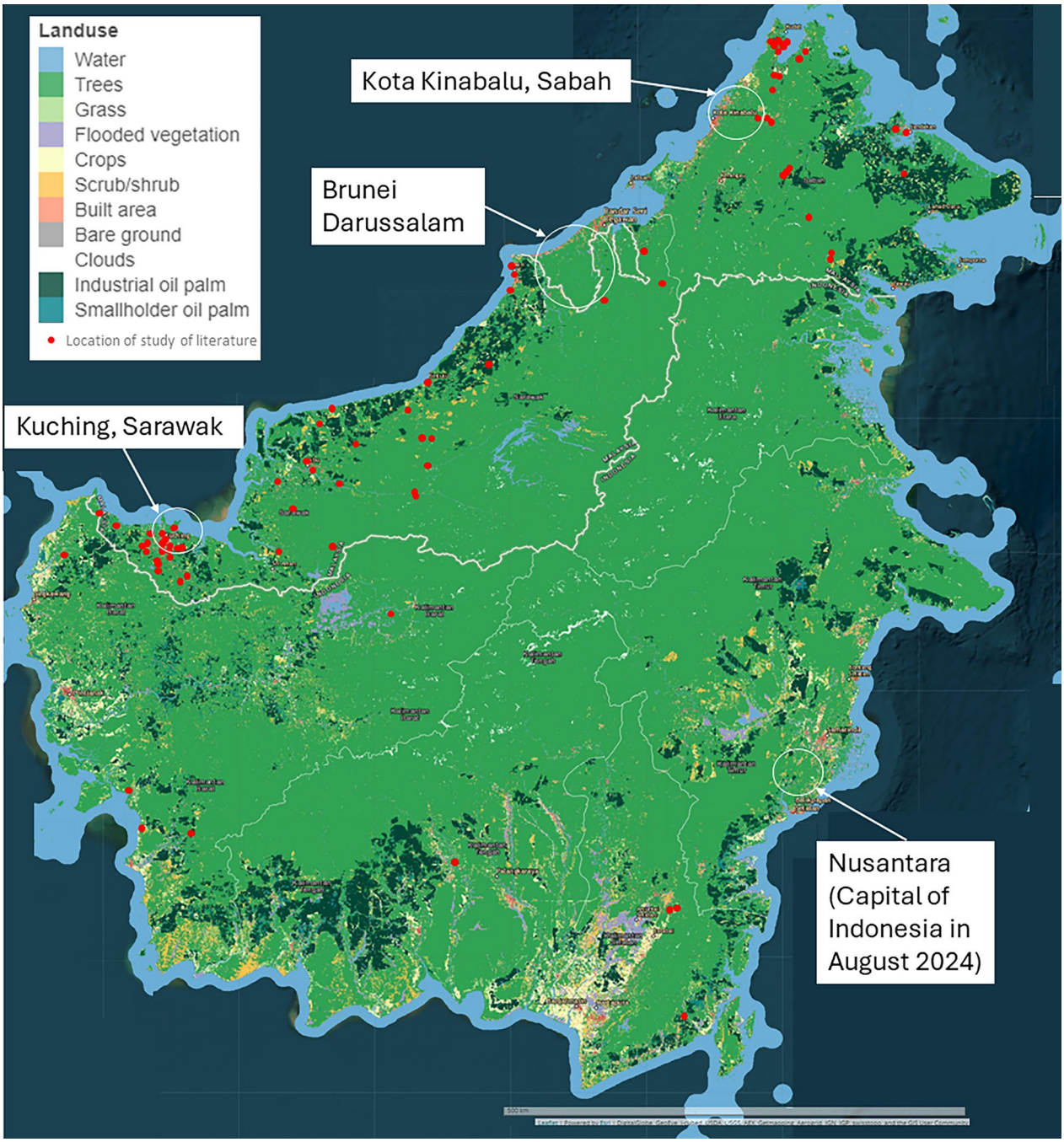

Fig. 5 The red dots represent the places of study mentioned in the literature reviewed, and the white circles and text boxes indicate some of the cities on the island of Borneo

For different vector-borne diseases, the components of the One Health approach are weighed differently. For example, tick-borne diseases such as Lyme disease always involve an animal host before the disease is transmitted to humans [33], so understanding the disease is also critical to its management. Figure 6 illustrates the composition of the literature analysed according to the One Health approach. Sixty-two per cent of the material focused on the human component, either on clinical treatment, molecular studies or surveillance to prevent the transmission of pathogens to humans. Second was animal health, which accounted for 28% of the literature

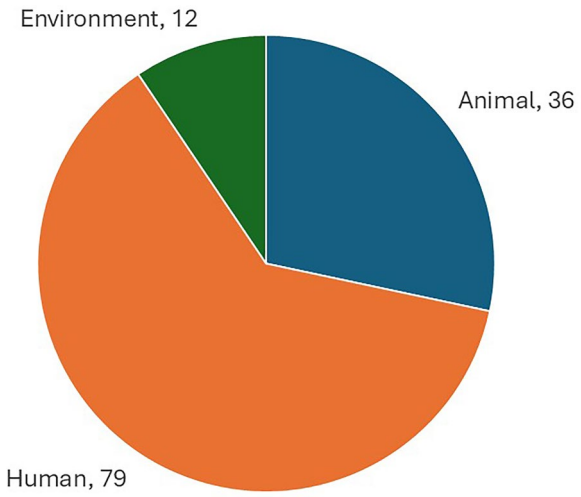

Fig. 6 The composition of the literature is based on the elements of the One Health approach. The chart was labelled with the t followed by the number of the literature. There were some articles that focused on more than one element of the One Health approach and were considered related elements

and focused mainly on possible zoonoses, ectoparasites and the vector itself. Wildlife was probably the key to vector-borne diseases in Borneo, where most diseases originated from wildlife (e.g., Zika). Therefore, for future studies on enzootic or zoonotic diseases or spillover animals, the type of animal involved was also indicated in Table 1.

The environment was probably the most important element on which human and animal health are most dependent. For example, climate change affects the frequency of rainfall and thus habitat availability [34]; temperature increases the growth rate of vectors such as mosquitoes [35]; and the migration of animals (rodents and monitor lizards [36]) carrying vectors such as ticks, mites, and lice to habitats more suitable for humans. Twelve of the literature focuses on the environmental element that has been least researched. Within this literature, nine articles focus on landscape changes that significantly affect the spread of vectors and thus disease transmission.

Discussion

The large number of malaria studies may be due to a possible resurgence of human malaria [37], and the emergence of zoonotic malaria (due to the species *P. knowlesi*, *Plasmodium cynomolgi*, *Plasmodium fieldi* and *Plasmodium inui*) in Borneo is being closely monitored [38]. Therefore, intensive studies have been conducted to learn more about transmission, especially the problem of spillovers from wildlife species where zoonotic transmission becomes sylvatic [39, 40]. Although dengue ranks second in the literature, the number of studies is relatively small compared to Peninsular Malaysia and neighboring countries such as Thailand and the Philippines. The large difference in the number of studies on malaria could be due to the unique landscape of Borneo, which still consists of many undeveloped areas such as protected forests and rural areas that provide an ideal habitat for *Anopheles* mosquitoes. However, rapid changes in land use in Borneo, particularly rapid urbanization [41, 42] and increasing forest disturbance from various activities, such as logging, poaching and ecotourism [43], are reflected in the increase in dengue cases in Borneo. The highly neglected mosquito-borne diseases such as Zika virus (with only one study [44]) should be emphasized. The first outbreak of indigenous Zika virus in Sabah, Malaysian Borneo, and Chikungunya (no literature in this study period) nevertheless posed a significant threat to Borneo. However, the relative paucity of literature on other vector-borne diseases could be due to several factors. To understand vector-borne disease transmission, the landscape and land use of Borneo needed to be understood. The island was once covered with dense rainforests and swampy coastal areas fringed by mangrove forests and a mountainous interior. As much of the terrain was virtually impassable and unexplored, surveillance work was made difficult [29]. With increasing urbanization and demand for electricity, deforestation and forest modification increased, ultimately increasing human contact with the native host and vector and, most importantly, zoonotic transmission. Therefore, some of the gaps and challenges also were summarized in this study.

Gaps and challenges

Highly neglected vector-borne diseases

There is a notable gap in the understanding and management of vector-borne diseases other than malaria. For example, efforts to monitor and control Zika and Chikungunya are very limited. Recent studies on Zika virus have highlighted the high prevalence of Zika virus in the serum of the local community [45]. Similarly, there has been an outbreak of Chikungunya in neighboring landscapes such as Peninsular Malaysia in 2007 [46] and Penang Malaysia in 2022 [47]. It is worth noting that people from Peninsular Malaysia frequently travel to Borneo and thus pose a high risk of transmission to Borneo. Indeed, Hotez et al. [48] mentioned the prevalence of sylvatic transmission of flaviviruses, including JE, which is already endemic in Borneo and requires consistent monitoring.

In addition, Borneo has many sandy riverbanks, wet beaches, seashores, and wetlands that serve as habitats for sandflies. Some reports have noted the large number of sandflies in certain parts of Borneo, such as Miri Sarawak [49]. However, both the vector and the disease

have been largely neglected. Although cases of leishmaniasis have been reported in Malaysia, it was introduced by an immigrant [50]. The most comprehensive study on Borneo was published in 1961 by Laurence et al. [25], although more recent studies on sandflies and pathogen surveillance have been conducted in neighboring landscapes such as Peninsular Malaysia, Thailand and the Philippines.

The challenges in controlling other vectors in Borneo may be due to limited resources and prioritization. Cases of Zika, Chikungunya, leishmaniasis/sandfly fever and tick-borne diseases are relatively under-diagnosed and under-monitored compared to cases of malaria and dengue. Another reason could be the asymptomatic nature of some of these diseases. Insufficient information about these vectors and diseases hinders the ability of public health practitioners to respond effectively to outbreaks and implement preventive measures.

Exploring other areas to understand the impact of human activities on the spread and distribution of vectors and pathogens

Human activities such as deforestation are probably the main reason for the displacement of native wildlife to other areas [51]. These wild animals serve as natural hosts and reservoirs for many pathogens that can be transmitted to humans. If the landscape changes, the vector responsible for the disease could also change its ecology and behaviour. Therefore, it is crucial that more areas be surveyed for vectors and pathogens, especially those areas that are to be urbanized or converted to agricultural land. Nevertheless, there are currently no guidelines or regulations for the assessment of vectors, except for the assessment of biodiversity in the area (including protected or endangered species). The second reason is that in resource-limited or geographically remote areas, it is a major challenge to effectively reach and monitor vector populations. These hard-to-reach areas may lack adequate infrastructure, health facilities or transport networks, making it difficult to conduct comprehensive surveillance and research activities. As mentioned in Ong et al. [29], these remote areas require support from electricity to recharge the traps and a freezer to preserve the pathogen's nucleic acid for screening.

As a result, there is limited understanding of the dynamics of vectors and pathogens in these regions, complicating efforts to control disease transmission and implement targeted interventions. For example, Fornace et al. [52] conducted a longitudinal study in Kudat Sabah in northern Borneo, covering most of the local community area. However, further efforts are still needed to identify *Plasmodium* in *Anopheles* mosquitoes and determine the biodiversity of both the pathogen and the vector. In addition, Young et al. [53] and Adrus et al. [31] conducted surveys of rodent ectoparasites collected in Kuching Sarawak and surrounding areas. However, studies suggest that other major cities in Sarawak should also be surveyed to obtain a more comprehensive picture of their distribution. However, to understand the boundary between sylvatic and human transmission, more information is needed on inland forests, coasts and islands. This could be due to limited logistical capabilities and facilities, such as freezers, that can maintain the cold chain for pathogen screening. To minimize this gap, innovative approaches, and increased investment in strategies to reach and engage populations in remote or marginalized areas are needed.

There is a strong focus on animal and human elements, while the environment has been severely neglected

Traditional approaches to the study of vector-borne diseases have often focused on the interactions between pathogens, vectors and human hosts, overlooking the crucial role of environmental factors. Environmental conditions such as climate, land use, habitat destruction and urbanization have significant impacts on the occurrence, spread and dynamics of vector-borne diseases. However, there is a tendency to neglect the environmental dimension and focus on animal and human health aspects. For example, White and Razgour [54] have shown that changing land use significantly alters the distribution of long-tailed macaques, bringing this natural host of *Plasmodium* spp. closer to humans. Another challenge in studying the environmental element of One Health could be the derivation and collection of data. This means that the relationship between the environmental factors and the vector or transmission can be investigated before the environmental variables are defined. Defining the variables is a challenge that depends on the research question to be answered but is often time consuming and costly. For example, Brown et al. [30] collected blood samples and interviewed people in a village individually to understand host behaviour (e.g., farming activities) in relation to exposure to zoonotic *Anopheles* mosquitoes; therefore, a well-defined first-hand research question was crucial. Byrne et al. [55] collected the larvae of *Anopheles* mosquitoes and used remote sensing data to collect environmental data and investigate the risk factors for Anopheles mosquito breeding sites. With further advances in remote sensing, more data can be collected, which ultimately requires proper data management and more robust modelling, such as machine learning [56]. More environmental data and robust modelling should help us understand and address the complex environmental factors that cause vector-borne diseases. Finally, this study emphasized the importance of incorporating

the environmental perspective into vector-borne disease research, policy, and practice.

Conclusion and future directions

The literature on vector-borne diseases in Borneo from 2017 to 2023 was reviewed and discussed. Malaria is the most studied disease in the region. Nevertheless, there are still gaps in malaria research, and further studies are needed to confirm the possible transboundary differences in human activities in forested areas or, more importantly, the possibility of human-to-human transmission. Under the One Health approach, further details should be defined to guide assessment and surveillance. The concept of One Health has gained traction in the public health debate. However, there is still a need for more specific guidelines and standards for practical implementation in the context of surveillance and control of vector-borne diseases. Defining clear indicators, methodologies and benchmarks within the One Health framework is crucial for guiding assessment and surveillance activities, facilitating interdisciplinary collaboration and providing information for evidence-based interventions. To address this gap, concerted action is needed to develop comprehensive guidelines that consider the complex interactions between human, animal and environmental health in the context of vector-borne diseases.

Therefore, some possible future directions are presented below in this study:

1. More research on surveillance of Zika virus, dengue fever (different serotypes), chikungunya, JE and Hanipah virus using next-generation sequencing (NGS) or real-time qPCR multiplexing techniques that can detect multiple viruses in one (pooled) sample.
2. Develop surveillance systems that specifically target flaviviruses in regions where they are endemic or emerging to improve early detection and response.
3. Provide resources for capacity-building initiatives to enable local communities to effectively monitor and respond to vector-borne diseases.
4. Establish a One Health assessment and surveillance framework that includes specific indicators, methodologies and benchmarks for assessing the interconnectedness of human, animal and environmental health.
5. Conduct pilot studies to demonstrate the practical application of One Health principles in addressing specific vector-borne diseases or environmental health problems.
6. Continuously review and update One Health Guidelines based on new scientific knowledge, technological advances and lessons learned from interdisciplinary collaboration.
7. More robust models and tools, including machine learning, should be developed to assess the impact of environmental factors such as climate change, land use and habitat degradation on vector populations and disease spread.
8. Promote collaboration between environmental scientists, public health professionals and policy makers to develop holistic approaches to disease prevention and control.

Supplementary Information

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Supplementary Material 1.

Author contributions

Song-Quan Ong: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft, writing—review & editing, visualization, supervision, project administration, funding acquisition. Ag. Shazmeer Bin Ag Safree: conceptualization, methodology, validation, writing—review & editing. Nur Badriah Binti Asmail @ Ismai: conceptualization, validation, writin—review & editing.

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Declarations

Competing interests

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