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Viewpoint

Adopting a Statistical, Mechanistic, Integrated Surveillance, Thermal Biology, and Holistic (SMITH) Approach for Arbovirus Control in a Changing Climate: A Review of Evidence

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Citation: Oladipo, H.J.; Tajudeen, Y.A.; Oladunjoye, I.O.; Mustapha, S.T.; Sodiq, Y.I.; Yusuf, R.O.; Egbewande, O.M.; Muili, A.O.; Adigun, T.O.; Taiwo, E.O.; et al. Adopting a Statistical, Mechanistic, Integrated Surveillance, Thermal Biology, and Holistic (SMITH) Approach for Arbovirus Control in a Changing Climate: A Review of Evidence. *Challenges* **2023**, *14*, 8. https://doi.org/10.3390/challe14010008

Academic Editor: Susan Prescott

Received: 8 October 2022
Revised: 15 January 2023
Accepted: 17 January 2023
Published: 22 January 2023

Abstract: Arbovirus control depends on accurate projections of likely changes in the arthropod vector species, essential to inform local and global public health authorities. According to the WHO Assembly and the Global Vector Control Response (GVCR), by 2030, the burden of vector-borne diseases, particularly arbovirus infections, is expected to be greatly decreased. However, anthropogenic drivers, including climate change, insecticide resistance, and a lack of operational local databases for risk management of emerging and re-emerging arboviruses, hinders effective implementation plans. This article presents a statistical, mechanistic, integrated surveillance, thermal biology, and holistic framework (termed SMITH) to discuss how temperature variations affect the biological transmission, replication, extrinsic incubation period, nutritional behavior, distribution, and survival (TRENDS) of arboviruses. Future transdisciplinary research that involves knowledge translation between local and global communities is required for early detection and risk management of the growing threat posed by arboviruses for human, animal, and planetary health.

Keywords: arbovirus control; climate change; Global Vector Control Response; integrated surveillance; planetary health

1. Introduction

Arboviruses or arthropod-borne viruses are a taxonomically diverse group of viruses transmitted to their vertebrate host by arthropod vectors. These vectors are predominantly mosquitoes (especially Aedes species: *Aedes aegypti* and *Aedes albopictus*) and ticks. Other vectors include sandflies, midges, and insect bugs [1]. In general, arboviruses circulate regularly in wildlife, livestock, and humans, leading to increased morbidity, mortality, and a great socioeconomic burden [1]. During the past decade, changes in climatic conditions have been reported to contribute to the emergence and re-emergence of medically important arboviruses. These arboviruses include the West Nile virus (WNV), the Dengue virus

(DENV), and the Chikungunya virus (CHIKV), with raising concerns about a global public health threat [1]. Most of these arboviruses responsible for human diseases are attributed to one of the following families, namely, Togaviridae (genus Alphavirus), Bunyaviridae (genera Orthobunyavirus, Phlebovirus, and Nairovirus), Flaviviridae (genus Flavivirus) and Reoviridae (genera Orbivirus and Coltivirus) [2,3]. However, key biological components of zoonotic arboviruses can collectively be examined under the acronym 'TRENDS' (T: transmission of viruses, R: replication of viruses, E: extrinsic incubation period of viruses, N: nutritional behavior of vectors, D: distribution of vectors, and S: survival of viruses) [4]. This is because arthropod vectors are poikilotherms, and their internal temperature is regulated by changes in the ambient temperature condition [5]. Changes in atmospheric conditions from day to day, and hour to hour, differ from climate, which is defined as the average of weather conditions (e.g., temperature and rainfall) over time [6]. Despite assessments of the effects of global climate change on vector-pathogen episystems, there has been little attention linking the effects of climate change on zoonotic arboviruses' biological dynamics. Although, arboviruses usually have geographically restricted distributions, however, with rising global temperatures, vectors spread, and the viruses they transmit, propagation to new areas is more likely, as reported in some studies [5,6]. Since the Intergovernmental Panel on Climate Change (IPCC) anticipates a future elevation of temperature above the 1.5 °C threshold for the coming decades [6], this will require a thorough understanding of factors that affect zoonotic arbovirus TRENDS and, consequently, effective public health measures for early detection, diagnosis, and management.

Furthermore, the underpinning anthropogenic drivers, such as urbanization, changes in land use, deforestation, and loss of biodiversity, have significantly affected arthropod vector habitat, lifecycle dynamics, and consequently, the vulnerability of animal and human populations to arboviral threats [7,8]. Prevention and control strategies are of great importance today in tropical and subtropical regions highly susceptible to the dual risk of climatic changes and arboviruses spread [9]. This requires addressing all these interconnected environmental and anthropogenic dynamics with a long-term implementation plan and a transdisciplinary approach, such as 'planetary health' [9]. Furthermore, coordinated statistical and mechanistic entomological surveillance studies that focus on thermal biology and how it influences the TRENDS of arboviruses can provide a meaningful database to track vector-borne and arbovirus spread across time and space [10]. For example, for each degree Celsius increase in temperature, a coupled affection in the dynamics of arbovirus transmission is expected, including *Aedes aegypti* and *Aedes albopictus*, the main vectors affected by climate change among the range of efficient vectors transmitting arboviral diseases [11]. This calls for the need to intensify surveillance with operable databases to gather, analyse, and predict vector species overlap in geographical areas where arbovirus risks are perceived as not common. This along with raising awareness among healthcare workers to broaden their diagnostic scope when treating febrile diseases of infectious vector-borne origin [10,11]. Hence, an integrated approach that takes into consideration unique temperature-dependent characteristics in the vector-virus life histories is a timely endeavor. Mathematical modeling studies along with epidemiological integrated surveillance, are also essentially needed in areas of emergence and re-emergence of arboviruses. In this article, the SMITH framework is suggested and described for early detection and implementation strategies in controlling arboviruses. This framework combines statistical, mechanistic, integrated surveillance, thermal biology, and holistic components that involve both One Health and planetary health approaches. Planetary health further promotes cross-sectoral and international cooperation with local stakeholders in response to the arboviral threat at the interfaces between the vector, the host, and the environment [9].

2. TRENDS of Arboviruses

In this context, the acronym TRENDS denotes the six important factors that contribute to the prevalence of arboviral diseases in human populations in light of the increasing global temperature. Although 'TRENDS' has been defined in the previous paragraph, it is explained below in detail.

2.1. "T: Transmission of Viruses" and Temperature

Arthropod-borne viruses (arboviruses) are among the infectious agents that are significantly influenced by temperature [11,12]. This has a profound impact on a variety of host, vector, and viral biological processes [11]. These biological processes consist of blood feeding and mating behaviors, vector competence, and lifecycle characteristics of immature stages and adult vectors [11]. However, these effects vary depending on the virus strain, population, and vector species [13,14]. Since arthropods are poikilothermic and very susceptible to temperature variations, as are the infections they carry, the effects of temperature on arboviral transmission are of particular concern [15,16]. Arbovirus transmission is often unimodally affected by temperature, with abundance increasing to an optimum and subsequently decreasing at high temperatures [11]. Although the arboviral transmission is accelerated at higher temperatures when vector competence increases, this rise in transmission at higher temperature would shorten the survival of the insect host, curtailing the duration of time it serves as a vector-transmitting agent [15,17,18]. Temperature changes can affect both the host and virus biology, making it difficult to predict the relationship between temperature and arboviral transmission [11,15]. Additionally, the complexity of enzootic transmission cycles makes understanding the role of temperature a challenge. However, with increasing global temperature and urbanisation, arboviral disease will continue to emerge and re-emerge [5,6].

2.2. "R: Replication of Viruses" and Temperature

Zoonotic arboviruses are composed of a variety of different viruses, each sharing a lifecycle that requires replication in both a vertebrate host and an arthropod vector [15]. Different factors can influence the ability of an arthropod vector to acquire and subsequently transmit a pathogen; however, every virus must overcome the barriers to replication and dissemination in the insect vector to be transmitted [15]. For example, arboviruses replicate at temperatures ranging from 37 to 44 °C [19], then switch to their poikilothermic vectors, where temperatures vary depending on the ambient temperature, which could be as low as 15 °C [16]. The fact that arboviruses tolerate such drastic temperature changes raises several questions, such as the effects of temperature on quasi-species, structures, and dynamics, the selection of temperature-adapted variants, and impacts on virus transmission, replication, and pathogenesis [16]. Temperature is known to induce molecular changes that affect lipids, nucleic acids, and protein structures and functions [20]. Therefore, it is highly likely that temperature modifies the properties of virions and their interactions with cellular components during replication [16]. Virus replication rates generally increase with temperature [15,16,21], that is, higher temperatures increase the replicative capacity of these viruses, leading to increased transmissibility [15]. Furthermore, there is evidence that exposure to cooler temperatures cripples the antiviral immune response of some arthropod vectors, allowing the virus to replicate at higher levels [22]. At lower temperatures, the ability of the vector to modulate the virus is compromised, allowing increased virus replication and transmission [23]. Since transmission and replication are correlated with viral load, lower temperatures are generally disadvantageous for arboviral transmission [16,21].

2.3. "E: Extrinsic Incubation Period of Viruses" and Temperature

After ingestion of a blood meal containing infectious virus particles by an arthropod vector, the midgut of the arthropod will become infected and then the virus can spread to peripheral tissues in the mosquito, where it can be amplified before reaching the salivary glands [15]. Successful infection and amplification of the virus in the salivary gland is a essential for virus transmission to the vertebrate host [15]. The time that elapses from ingestion of an infectious blood meal to virus transmission is known as the extrinsic incubation period (EIP). The EIP is highly temperature dependent and is often used as an index of vector competence. For a vector to successfully transmit a virus, the vector must first survive the EIP [6]. A study by Richards et al. showed that the relationship between infection rates and transmission changed according to temperature during the incubation period [24]. Their study also analyzed the relationship between infection and transmission changes under different EIP, suggesting that temperature affects infection and transmission differently [24]. However, exposure to cooler temperatures could cripple the antiviral immune response of some arthropods, such as mosquito species vectors, allowing the virus to replicate to higher levels, thus increasing the EIP of the virus, as lower temperatures negatively affect virus replication more than they affect the antiviral immune response in the insect vector [15,22].

2.4. "N: Nutritional Behavior of Arthropod Vectors" and Temperature

Nutrition is essential for the growth and development of arbovirus vectors and can have an impact on several pathways linked to vector susceptibility, viral load and burden, willingness to feed, and even vector control measures [25]. For example, mosquito larvae, which live in aquatic habitats, feed on organic detritus, bacteria, algae, protozoa, and other microorganisms, and derived nutrients, such as carbohydrates, minerals, protein, vitamin B complex, and fat, are vital for mosquito development and control measures [25].

Nutrition during the development stages can also affect the feeding behavior of adult mosquitoes. This affects the transmission of viral diseases and vector competence. For example, a study carried out with *Aedes triseriatus* and the La Crosse virus revealed that smaller female mosquitoes originating from larvae deprived of nutrients had significantly higher vector competence and higher oral transmission rates compared to their normal or overfed counterparts [26]. However, other studies have shown the opposite effect or no effect of mosquito size on vector competence [25]. Arthropods are particularly sensitive to changes in climate. They are also poikilothermic, which means that external environmental conditions regulate their internal temperature, which in turn impacts the rates at which they feed on and bite their vertebrate hosts [27]. In addition, according to previous research, vector biting rates tend to increase with temperature up to a certain point and then fall [12].

The critical link between temperature and mosquito feeding habits in other vector-borne parasitic infections can be drawn from a malaria study by Suh et al. [28]. This study carried out on how dietary habits interacted with environmental temperature to affect the mosquito's ability to spread *Plasmodium falciparum* [28]. The study reported a significant increase in the number of mosquitoes that feed in the evening (18:00) compared to the morning (06:00) and the middle of the night (00:00). This indicates that feeding was temperature-dependent, the vectors preferred feeding at cooling temperatures, and warmer temperatures inhibited the development of parasites [28]. However, vectors transmitting arboviruses, their feeding and biting habits in relation to variations in temperature warrants further research.

2.5. "D: Distribution of Arthropod Vectors" and Temperature

Since arboviruses are transmitted by insects that are poikilothermic and highly sensitive to temperature fluctuations, temperature role is vital in the dispersion of arthropod vectors and the transmissibility of arboviruses [15]. The biting behavior and level of activity of the vectors fluctuate with temperature, which can have an impact on the spread of arboviruses to vulnerable human and animal populations. Higher temperatures shorten the lifecycle of arthropod vectors, and this increases the number of vectors in a particular area, suggesting that arboviral diseases will continue to emerge and re-emerge with increasing global temperatures [15]. For example, *Aedes aegypti*, the main vector of several arboviral diseases, including Dengue, Chikungunya, Yellow fever, and Zika, is expected to increase in abundance and geographic scope as the climate of the world warms [29]. Although *Aedes aegypti* does not follow a linear pattern, there is a correlation between climate change and the spread of infectious diseases which requires a corresponding evaluation of the distribution and abundance of the arbovirus vector *Aedes aegypti* globally in several climate change scenarios. [15]. It was also reported that higher temperatures increase virus replication capacity, which then results in increased transmissibility [6]. For a few specific vectorborne arboviruses example, higher vector competence for arbovirus is associated with lower temperatures [27]. That is colder temperatures have been shown to hinder the antiviral immune response of some mosquito vector species, allowing the virus to proliferate at higher levels [15,22]. Caminade et al. explained that the development and replication of pathogens transmitted within vectors or in the environment occur faster at high temperatures [12]. Furthermore, a study by Wittmann et al. revealed that the duration of the EIP for the African horse sickness virus (AHSV) serotypes 4, the epizootic hemorrhagic disease of deer virus (EHDV) serotype 1, and the bluetongue virus (BTV) serotypes 10 and 16 (AHSV4, EHDV1, BTV10 and BTV16) in *Culicoides sonorensis* was generally shorter at higher temperatures [30], indicating that *C. sonorensis* would be able to transmit the virus faster at higher temperatures.

In general, temperature plays an important role in the distribution of vectors and the transmission of diseases. As the climate continues to change and temperatures fluctuate, further studies are needed to link the effects of temperature on vector distribution and implications for effective prevention and control of arbovirus diseases.

2.6. "S: Survival of Viruses" and Temperature

Climate can affect the dynamics of transmission, geographic spread, and re-emergence of vector-borne diseases through a variety of mechanisms, including direct impacts on the pathogen, the vector, animal, and human hosts [31]. According to Rocklöv et al., the rapid global warming caused by anthropogenic greenhouse gas emissions will have a significant impact on the long-term prevention and control of vector-borne diseases [31]. Additionally, temperature affects viruses and vectors in different ways. While higher temperatures can speed up the process of viral transmission, they can also shorten the survival of some insect hosts, thereby reducing the duration of time it serves as a vector [15]. Therefore, arboviruses must infect the arthropod vector at ambient temperatures, which may vary considerably depending on climate, season, and local conditions [27]. However, there is concern that as the Earth continues to warm, vectors and viruses will spread to higher latitudes and altitudes, causing an increase in incidence and a longer transmission season in some endemic regions [31].

Furthermore, because arthropods and other vectors are poikilotherms, it is expected that vector abundance, survival, feeding, and biting activity will increase with rising temperatures, as will the rate of development of the pathogen within the vector. This implies that insect vectors tend to thrive better at higher temperatures, and as a result, the effects of global warming will result in the emergence and re-emergence of vector-borne diseases [23]. However, while it is true that in general, warmer temperatures are preferable for vector survival, these correlations are frequently complicated. For example, one study revealed that the survival of the Dengue vector *Aedes aegypti* from the egg to the adult increases fairly linearly, from close to 0% at 15 °C to around 90% at 20 °C, before gradually decreasing to approximately 60% at 35 °C [31]. Temperature conditions have a substantial impact on vector development and survival along with the arbovirus it transmits [12].

3. The Statistical, Mechanistic, Integrated Surveillance, Thermal Biology, and Holistic (SMITH) Approach to Arboviruses

Global warming has been factored into models that predict changes in the distributions of *Aedes aegypti* and *Aedes albopictus*, as well as associated changes in vector-borne diseases [32,33]. However, Walter and colleagues stated that it is difficult to predict the future consequences of global climate change on arbovirus evolution because, for example, the factors that influence the evolution and diversity of DENV and YFV are diverse, complex, and lack the impact of long-term climate change [33,34]. This requires greater data gathering and mapping that predicts potential consequences of climate change on a wider range of arthropod species together with their arbovirus evolution. Therefore, this section discusses the statistical, mechanistic, integrated surveillance, thermal biology, and holistic (SMITH) approach as a proposed integrated framework for the early detection and control of arboviruses.

3.1. Statistical and Mechanistic Approach

Many species distribution models combine computer algorithms, data on species occurrence, climate conditions, and a variety of potential predictor variables, including vegetation and land use. These variables designed into models are used to predict the most favorable locations and habitat where arthropod vectors can thrive [35,36]. Subsequently, these models evaluate the ability of arthropod vectors to adapt to changing environmental conditions to inform future studies and control measures of specific vector-borne diseases [35,36]. The statistical model and the mechanistic model are the two most frequently applied models [35]. The statistical model correlates species occurrence data with environmental factors. It is typically used on a wide scale in time and space, needs to be trained on a fraction of the occurrence data and verified to constantly improve prediction results [36,37]. On the other hand, the mechanistic model simulates the process by which the physiology and behavioral traits of arthropod vectors evolve in response to changes in climate and land use [36]. Moreso, it simulates the process by which these changes occur, in a way that is favorable for colonization and spread of a specific arthropod in its suitable habitat [38,39]. There are numerous methods that integrate both the statistical and mechanistic models to create the needed powerful analytic techniques [35]. Currently, three different methods are applied to link the statistical and mechanistic approaches in a modelling framework, which will be discussed below.

The first method compares the results of statistical and mechanistic models for the same species of arthropod vector [40]. The results of the predictions of the two models will agree or disagree, and agreement between the models would imply a higher degree of confidence in the results [35].

The second strategy uses the mechanistic approach to produce outputs that are extremely related while making sure that variables such as potential feeding/activity time, aquatic stages, and developmental time for the given arthropod vector species are included within a particular terrain and vegetation [41,42]. The statistical model analysis would then be built using the predictions obtained from the mechanistic approach [35,41,42].

The third model, which combines both mechanistic and statistical techniques, uses the mechanistic approach to specify the geographic area of the statistical model. The mechanistic information is initially used to locate regions on a geographical landscape where the arthropod vector species do not occur, which is how this process is practically carried out [43]. The statistical model analyses are then narrowly concentrated in the regions where the arthropod vector species are present, and they are excluded from the regions where they are not [43].

From those three examples, combining the statistical and mechanistic approach into an integrated modeling framework would reduce uncertainty, errors, and bias in the generation of arthropod vector species projections [39,44]. As the mechanistic model relies on a wide range of model parameters, each with its own uncertainties and bias, errors in species projections are reported frequently in the mechanistic model over the statistical model [45]. Thus, an integrated modeling framework that combines statistical and mechanistic model techniques is more powerful and capable of producing a more accurate distribution of vector taxa species in a specific location [35,39,46]. Hence, arbovirus control relies heavily on accurate predictions of future arthropod vector species range shifts, which is needed to fully inform public health authorities [35,47].

3.2. Integrated Surveillance

One Health surveillance, also known as integrated surveillance, is the process of ‘systematically collecting, validating, analyzing, interpreting, and disseminating data on humans, animals, and the environment to inform the decision for more effective, evidence-based, and system-based health interventions' [48]. By 2030, the incidence and impact of vector-borne diseases are to be reduced by sustainable and locally tailored vector management, according to the Global Vector Control Response (GVCR), which was recently accepted by the WHO Assembly [31]. Curbing infectious diseases at the animal-human-ecosystem interfaces is the ultimate goal of integrated surveillance [31]. However, research and intervention data scarcity on local level and the reported evidence base for regional vector control of arboviral diseases is still inadequate [49]. This is especially true in areas where mosquitoes have developed resistance to widely used insecticides that involve the control of malaria and other vector-borne diseases in or around human habitation [49]. Moyes et al. documented 57 countries that have already reported or suspected resistance to at least one chemical class of insecticides in mosquito species, such as *Aedes aegypti* or *Aedes albopictus* [50]. Insecticide resistance is now recognized as a major threat to arbovirus control and has probably contributed to arboviruses re-emergence and spread in some parts of the world [51]. Integrated surveillance is considered a promising working strategy for improving the early detection of emerging arboviral diseases [52]. In addition to providing early-warning signals, it could contribute more effectively to accurate risk assessments (RA) by systematically integrating multiple sources of surveillance data (indicator- and event-based surveillance, case-based surveillance, vector surveillance, and virus and environmental data and information) [48]. However, effective arbovirus control strategies are hampered by difficulties with interoperable databases, adequate data collection, and analysis in sectors in some countries [52]. This limited capacity for early warning and risk assessment, which affects the prevention and control of arbovirus infections, is consistent with the acknowledged challenges of timely sharing data and information [53]. Furthermore, the vulnerability of a nation or a particular geographical location to the exposure and spread of arbovirus infections can also be determined using ad hoc indicators, which can be used in conjunction with other measures to prevent outbreaks and epidemics [54].Despite increasing evidence of the benefits of sharing surveillance data for public health, with well-documented examples of better results; vector-borne disease surveillance using the One Health approach is considered the best integrated system-based approach to date, but with some local implementation limitations [54].

3.3. Thermal Biology

To ascertain the effects of temperature on arbovirus transmission, it is necessary to identify the temperatures that best balance the trade-offs between various temperature-dependent features of arthropod vectors and viruses [6]. This requires examining the unique thermal characteristics of the life histories of the linked vector-virus development. Moreover, the viral transmission temperature constraints are to be identified, and the favorable thermal conditions accordingly [5]. Most physiological traits and life history of vectors are reported to be non-linearly temperature sensitive, rising exponentially from zero at a thermal minimum to an optimum, before falling back to zero at a thermal maximum [55]. More research is needed for correlating vector competence, extrinsic incubation period, and vector survival, how newly evolved arboviruses appear in new geographic areas, and how this is related to transmission and temperature patterns [54].

3.4. Holistic Approach

The (re)emergence of human infections in animal reservoirs, as well as the impact of environmental and climate changes on the transmission of various infectious diseases, are discussed above in integrated surveillance using the One Health (OH) approach [5]. People, animals and the shared environment all benefit from OH, as a collaborative, multisectoral and transdisciplinary approach to improving health [53,54]. However, the baseline of human and animal health is significantly influenced by anthropogenic environmental dynamics and vitality. These interconnected challenges are highlighted in the principle of planetary health (PH) which encompasses the interface between the entire ecological theatre, including the vector, pathogen, animal, human hosts, and the local environment that sustain them [10]. A planetary health approach acknowledges the role of indigenous communities and local stakeholders in early detection, proper risk management, and relevant policy implementation [10]. Thus, managing emerging and re-emerging arboviral disease epidemics calls for a comprehensive strategy. A grassroots effort that considers the vector–host–environment interface together with the integration of the analytical, epidemiological, and entomological surveillance. This alongside with involvement of experts from various fields to carry out transdisciplinary and evidence-based research aimed at improving vector-borne disease prevention and control at a local and global scale.

4. Recommendations and Conclusions

The potential threat posed by arbovirus emergence and re-emergence in the era of climate change demands a synchronized local, national, and worldwide effort [56]. According to projections made using mathematical modeling, more than a billion people will be at danger of developing their first arbovirus infection during the next century [57].

From this standpoint, there is still a considerable gap, as few local longitudinal studies are conducted in areas where the emergence of arboviruses is occurring or is expected to occur [58]. Stewart et al. emphasized the need for more regional research to make the informed decisions required for the control of arboviruses in a changing environment [59]. Similarly, Ryan et al. stressed that to prevent more than 3 million Dengue cases per year in the Americas, measures to restrict climate change to 1.5 °C would be better than no intervention (+3.7 °C) at all [57]. Therefore, a fully implemented climate change mitigation strategy would protect a billion people from the development of arbovirus diseases [57].

Despite claims that climate change would likely lead to geographical changes rather than catastrophic effects on the populations of humans and animals, healthcare systems, and economies at risk of arboviruses [60,61]. There is still a need to strengthen both epidemiologic and entomological surveillance in areas of the emegence of arbovirus and establish sentinel surveillance sites in areas of possible future emergence. There are limited studies till date that correlates Chikungunya and Zika viruses to climate change, virus evolution, and epidemiology in a way that highlights the need for policy-relevant actionable recommendations [57,58].

As there are currently gaps in precise point of care diagnostics, targeted drug therapy, highly effective vaccines, and vector control strategies for arboviruses, it is more challenging to prevent, diagnose, and treat such diseases [57]. Undoubtedly, investing more meaningfully in arbovirus research and development would be a step in the right direction. For instance, among arthropod-borne diseases, malaria has received far more research and development attention in the past century. Considerable funding has been invested in eradicating *Plasmodium falciparum* through surveillance, vaccine development, drug discovery, and vector control interventions. These control efforts includes mass distribution campaigns for long-lasting insecticide nets (LLIN) and indoor residual spraying. Although eradicating malaria species is still of utmost importance, it is also vital to advance public health initiatives to better prepare for the potential emergence of arboviruses, especially in low-resource countries at risk of climate change negative consequences [57,62].

While surveillance shows that the Dengue virus accounts for close to 10% to 20% of febrile diseases in children in areas of high malaria endemicity in Kenya, and its vector, *Aedes aegypti,* was prolific in and around households throughout the year [57,63,64]. Likewise, Chikungunya epidemics have occurred in three different regions (Mombasa, Mandera, and Lamu) in Kenya and the Kassala state in Sudan, with other increasing evidence indicating that the epidemic and endemic transmission of arboviruses occur regularly in sub-Saharan Africa but are often undiagnosed or misdiagnosed as malaria cases [64,65]. This evidence indicates that arboviruses and their vectors are already rife in sub-Saharan Africa, but largely misdiagnosed or under-recognized to public health authorities.

Planetary health offers a comprehensive framework that identifies ecological and anthropogenic drivers related to climate change at the intersections of various biodiverse species. It also encompasses the environment that sustains insect vectors and host species for a better understanding of the dynamics in the emergence and re-emergence of arboviruses [10]. This could illuminate pathways to more coordinated transdisciplinary research that involves a wider range of scientists, policymakers, local stakeholders and healthcare professionals [8,59,66]. Arbovirus risk management strategies should begin at the subnational, national, regional, and global levels, respectively, along with the use of effective models to evaluate early detection and adequate responses.

Author Contributions: Conceptualization, H.J.O., Y.A.T. and I.O.O.; methodology, H.J.O., Y.A.T. and M.S.E.-S.; resources, H.J.O., Y.A.T., R.O.Y., I.O.O. and M.S.E.-S.; data curation, H.J.O., Y.A.T., I.O.O., S.T.M., Y.I.S., R.O.Y. and M.S.E.-S.; writing—original draft preparation, Y.A.T., H.J.O., R.O.Y., I.O.O., S.T.M., Y.I.S., O.M.E., A.O.M., T.O.A., E.O.T. and M.S.E.-S.; writing—review and editing, Y.A.T., H.J.O., I.O.O., E.O.T. and M.S.E.-S.; supervision, M.S.E.-S., Y.A.T., H.J.O. and I.O.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors appreciate the editor and reviewer(s) of the journal for their suggestions in improving the quality of the manuscript.

Conflicts of Interest: Emmanuel O. Taiwo has contributed to this work in a personal capacity, and the views expressed in this article do not represent the views of FCDO.

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