Arbovirus Vectors of Epidemiological Concern in East Africa: A systematic review of entomological studies (1940-2020)

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Source of funding: The Consortium for Advanced Research Training in Africa (CARTA) provided funding for the review and publication of this article

Summary

BACKGROUND

Emerging and re-emerging arboviral infections are increasing global public health concerns due to their rapid geographical spread and burden. In the East African region, knowledge of the diversity and distribution of their shared vectors remains incomplete. This review summarizes the state of the entomological studies on the mosquito vectors of arboviruses such as Yellow Fever, Rift Valley Fever, Zika, Dengue and Chikungunya fever viruses and the risk factors affecting virus transmission. The rationale of this systematic review was to characterize entomological studies that have been conducted in the East African region and establish the trend of epidemics of various arboviral infections from 1940-2020 to fill the existing knowledge gap.

MATERIAL AND METHODS

A systematic search was conducted using PubMed, Science Direct and bioPreprint to identify eligible studies using search terms: Yellow fever, Dengue, Chikungunya, Rift Valley Fever, arboviruses AND vectors in East Africa. Others were: Aedes, Culicine mosquitoes AND Tanzania/ Kenya/ Rwanda/ Uganda/ Burundi/ Sudan.

RESULTS

A total of 126 studies met the systematic review criteria. From 1940 to July 2020, a total of 389 arbovirus vector mosquito species have been described including 35% Aedes, 31% Culex, 12% Anopheles, 8% Coquillettidia, 5% Taeniorhynchus, 2% Eretmopodites and 7% other genera. The diversity of arbovirus vectors was highest in Kenya (151 spp) followed by Uganda (102 spp), Sudan (90), Tanzania (38 spp), Rwanda and Burundi recorded with only a few species.

CONCLUSION

Based on this review, we compile a database on arbovirus vector distribution paired with the viruses they transmit in the East African region. The vector species appear to be the same in the region and this calls for developing a strategic regional surveillance system for the prevention and control of future arboviral infections epidemics.

Keywords: *Arbovirus vectors, Vector distribution, Arboviruses, Mosquito-borne viruses, Epidemics, East Africa, Aedes mosquitoes, Culex mosquitoes*

[***Afr. J.*** *Health Sci*. 2022 35(4): 496-520]

Introduction

Emerging and re-emerging arboviruses (arthropod-borne viruses) in many tropical and subtropical regions of the world are a significant burden to public health. Arboviruses such as Dengue (DENV), Yellow fever (YF), Japanese encephalitis (JE), Chikungunya (CHIKV), West Nile Encephalitis (WNE), West Nile Virus (WNV) and Rift Valley Fever (RVF) have caused notable epidemics, leading to human and animal morbidity and mortality worldwide [1]. CHIKV, WNV and DENV are three major neglected human arboviral infections whose combined figures for morbidity and mortality far exceed those for Ebola, Severe Acute Respiratory Syndrome and Middle East Respiratory Syndrome Viruses [2]. Dengue fever alone for example affects almost 400 million people worldwide per annum [3] of which an estimated 22 000 people die each year [4].

The East African region has experienced several outbreaks of YFV, RVFV and recently DENV and Chikungunya, most of these infections are caused by viruses spread by insect vectors that spilt over from sylvan (forest) transmission cycles involving non-human primates to urban (domestic and peridomestic) transmission cycles involving human being [5]. Many of these viruses are zoonotic, and the term arbovirus describes the requirement of an arthropod vector for infection to occur [6, 7]. Arboviral infections are maintained in an epizootic cycle through the survival of the viruses in mosquito eggs mainly female aedine species. Notably, arthropod vectors are more important for the survival of arboviruses from season to season and serve as reservoir hosts [8]. Many arthropods such as mosquitoes, ticks, sand flies, midges and other bugs can be infected by viruses; however, the most prominent ones are ticks and mosquitoes and this review focuses on the latter. Approximately 300 species of mosquitoes are capable of transmitting viruses and these are mainly from Culex and Aedes genera associated with 105 and 115 arboviruses respectively [9, 10]. Mosquitoes in the Aedes genera mainly *Aedes aegypti* and *Aedes albopictus* have been implicated as the main vectors of arboviruses globally. The secondary arboviruses vectors incriminated in East Africa and elsewhere include species from Anopheles, Culex, Coquillettidia, Taeniorhynchus, Eretmopodites, Uranotaenia, Ficalbia and Mimomyia genera [11-14].

The emergence of arboviruses is thought to be largely driven by climate change, international travel and trade, increased contact between humans and wild or domesticated animals, an explosion of the human population, and unplanned urbanization that favours the breeding and proliferation of arthropod vectors [15]. The rapid succession and recent epidemics of arbovirus diseases, such as YF, RFV, DENV and CHIK in East Africa serve as reminders of the dramatic manner in which these arboviruses continue to emerge and spread with serious international public health consequences. In the East African region, climatic change, and unplanned urbanization combined with efficient vectors are some of the factors believed to be driving the emergence [16]. There is also a growing concern because most of these arboviral infections have no vaccines and or proper diagnosis and treatment, worse still countries in East Africa lack policies for the prevention and control of these diseases. Given the climate and geographic setting of the East African countries, there is a potential for spreading vectors and exchange of arboviruses through the movement of people, cargoes and trade goods among member states [17].

The East African Community (EAC) was initially founded in 1967 by three member states: Tanzania, Kenya and Uganda. The community was later dissolved in 1997 but was reconstituted again in the year 2000, Burundi and Rwanda joined the community in 2007 and lastly South Sudan which joined in the year 2016, the region has a total surface area of 1,817.7 thousand square kilometres [18]. The East African climate is of equatorial regions characterized by thick forests such Zika, Semliki and Bwamba in Uganda, river line forests such as Tana, Kakamega and Taita Hills in Kenya as well as coastal forests in Kenya and Tanzania. The unique geography of the EAC region is also constituted by various streams and rivers making it suitable for agriculture. Most rivers and streams are often characterized by irrigation-supported agriculture together with the tropical forests they create aquatic microhabitats suitable for mosquito breeding including vectors of arboviruses [19]. Many arboviruses of African origin have been isolated from vectors collected from Zika, Semliki, Uganda, Bwamba, Taita-Taveta and Tana forests [12, 20-23]. Although research on the fundamentals of arboviruses and the incrimination of vectors has been intensified following various epidemics in EAC, information on the distribution of common arbovirus mosquito vector species is lacking. The aim of this study, therefore, was to review the available information on arbovirus vectors of epidemiological concern in East African countries described between 1940-2020. Furthermore, it aimed to establish the trend of arboviral infections outbreaks, emerging and re-emergence of the viruses for the past 60 years. The compilation presents information on species composition, distribution, taxonomy, and infection status and also gives highlights on the trend of arbovirus epidemics. Some of the mosquito vector species presented could have been collected from Sudan as a whole and not South Sudan. The reason being South Sudan used to be part of Sudan until 9 July 2011, when South Sudan (currently the Republic of South Sudan) gained independence [24]. This comprehensive information is useful for the control of future epidemics and the design of joint surveillance vector control programs in the region.

Materials and Methods

Literature search

We conducted a systematic search for articles published between 1940 to June 2020 using PubMed and Science Direct to identify all potentially eligible entomological studies on arbovirus vectors. The database search was complemented with 'grey literature,' by reviewing the references listed in identified publications. In addition, the preprint manuscripts were accessed using the pre-print search web tool search.bioPreprint to retrieve preprints from PeerJ, arXiv, bioRxiv, and Wellcome Open Research. The search terms included the following: Yellow fever, Dengue, Chikungunya, Rift Valley Fever, arboviruses AND vectors in East Africa. Other terms included; Aedes mosquitoes, *Aedes aegypti*, Culicine mosquitoes AND Tanzania/ Kenya/ Rwanda/ Uganda/ Burundi/ Sudan. The year 1940 was chosen as a starting point for our search to reflect the timing of the emergence of many arboviruses (YFV, ZIKV, CHIKV and RVFV) in the region. To avoid bias two reviewers AP and SLL performed the search and reviewed the title and abstract independently. The results were compared and then compiled. A literature search was conducted between May to July 2020.

Inclusion criteria

- Primary studies on vector ecology, species composition, species distribution, vector competence, vectorial capacity, feeding preferences, infection status, abundance, density and virus transmission dynamics.
- Availability of primary data and articles published in English.

Exclusion criteria

- Studies on arbovirus vectors other than mosquitoes such as ticks and flies
- Studies conducted in countries other than the East African region
- Studies on secondary data analyses.
- Studies on seroprevalences in humans and animals

Results

A total of 1027 records were retrieved from the search, after screening titles and abstracts 743 records were not deemed relevant. Full-text screening of articles was performed on 284 articles to assess their eligibility and relevance to the topic. A total of 126 articles met the inclusion criteria and were included in the systematic review (Figure 1). Most of the published articles were conducted in Kenya (37.3%) followed by Uganda (35.7%), Tanzania (16.7%), Sudan (8.7%), Rwanda and Burundi constituted 0.8% each (Table 1). Studies to incriminate YF vectors were numerous between 1940-1960s (Figure 2), whereas studies on RVF vectors were mainly conducted between 1970-2000s. There was a sharp increase in entomological studies between the year 2010-2020 to characterize and incriminate a range of arboviruses notably DENV, CHIKV, RVFV, ONN and WNE in mosquito vectors. Other arboviruses such as Ntaya, Sandbis, Babanki, Mengo and Pangola have also been reported from various parts of the East African Region.

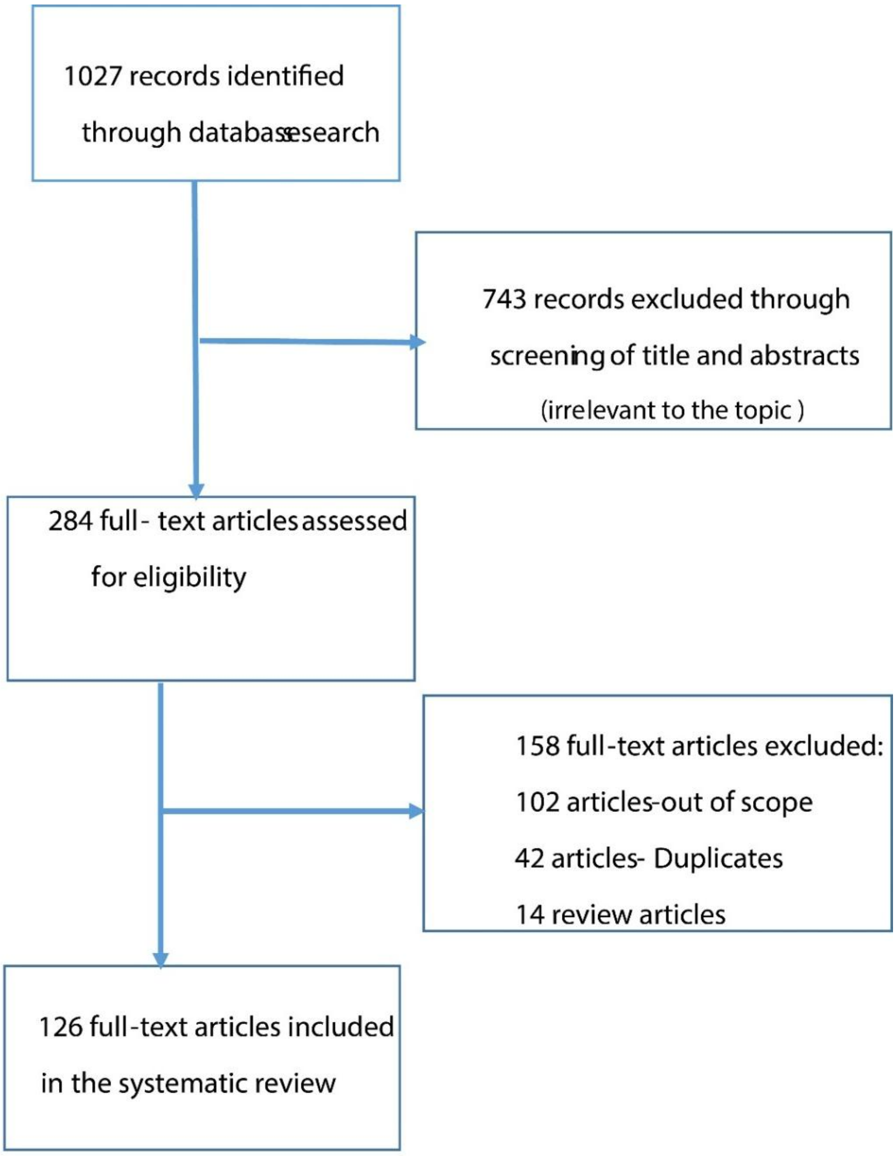

Figure 1: Flow chart of screening and exclusion steps of this systematic review and the resulting number of publications after each step

Fauna composition

Figure 3 shows some mosquito species vectors of various viruses that have been described among the EAC member states between 1940-2020. A total of 389 mosquito species have been described, of these 151 species have been documented in Kenya, 102 species in Uganda, 90 species in Sudan, 38 species in Tanzania, 5 species in Rwanda and 3 species in Burundi. The classification of this fauna into specific genera is presented in Table 1. Species in the Aedes and Culex genera constitute 35% and 31% respectively, others were Anopheles (12%), Coquillettidia (8%), Taeniorhynchus (5%), Eretmopodites (2%) and other genera constituted (7%). In all the 126 studies analysed, the most common data were species identified, abundance, year and place of sampling. Only 36 studies reported natural infection of mosquito vectors by arboviruses.

Vector infection status

Information on vectors which were found naturally infected with viruses is present in Table 2. Many studies attempted to isolate arboviruses from their respective vectors especially during epidemics to establish hotspots but only 36 studies in this review report infections in wild mosquitoes. Five studies report exclusively on *Ae. africanus* infection by Zika virus [25-28]. Zika viruses have also been isolated from *Ae. apicoargenteus* [26] in Zika and Lunyo forests, Uganda. Similarly, YFV has been isolated from *Ae.simpsoni*, *Ae. africanus*, *Ae. keniensis and Ae. aegypti* mosquitoes [29-32]. Furthermore, *An. gambiae* s.l *and An. funestus* s.l and *Mansonia uniformis* have been incriminated in the transmission of O'nyong-nyong virus (ONNV) [33, 34] and co-infections of flavivirus and orthobunyaviruses have been reported in *Cu. vansomerini* [13] and infection of male *Cu. univittatus* by WNV[35] in Kenya suggesting vertical transmission of the arbovirus. Nevertheless, many studies indicate that mosquito species can vector a range of viruses as indicated in Table 2. For example *Ae. aegypti* has been found naturally infected with CxFV, ISFVs, DENV, YF, RVFV and Chikungunya viruses [14, 36-38], similarly *Ae. mcintoshi* has been found naturally infected with BUNV, Pongola, NDUV, SFV BBKV, USUV, RVFV, CFAV and Ngari viruses [39-41]. Furthermore, NDUV, BBKV, SFV, and West Nile Viruses have been isolated from *Ae. sudanensis* [40, 42] in Kenya.

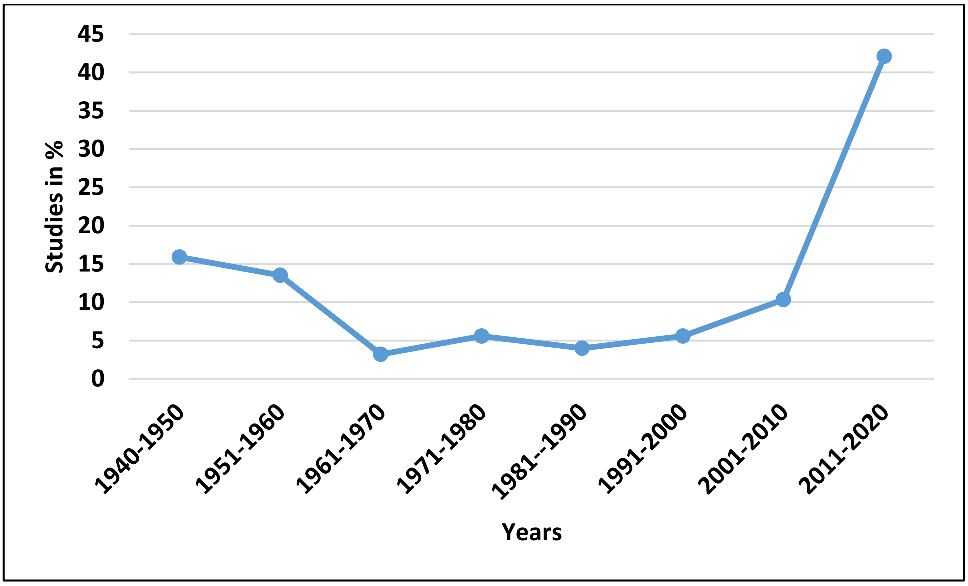

Figure 2:
The trend of entomological studies on arbovirus vectors in East Africa between 1940- 2020

Fifteen studies reported natural infection by arboviruses such as Pangola, and RVFV among Culex mosquitoes [12-14, 23, 35, 36, 40, 42-49]. Smithburn and Haddow [47] reported natural infection by Ntaya Virus in mosquitoes from genera other than Culex and Aedes such as *T. pseudoconopas*, *Ur. alboabdominalis*, *T. fraseri*, *T. aurites* and RVF virus have been isolated from *Mansonia uniformis* [41, 48] and from *An. squamosus*, *Mansonia Africana*, *An. christyi* and *An. pharoensi* [48, 49].

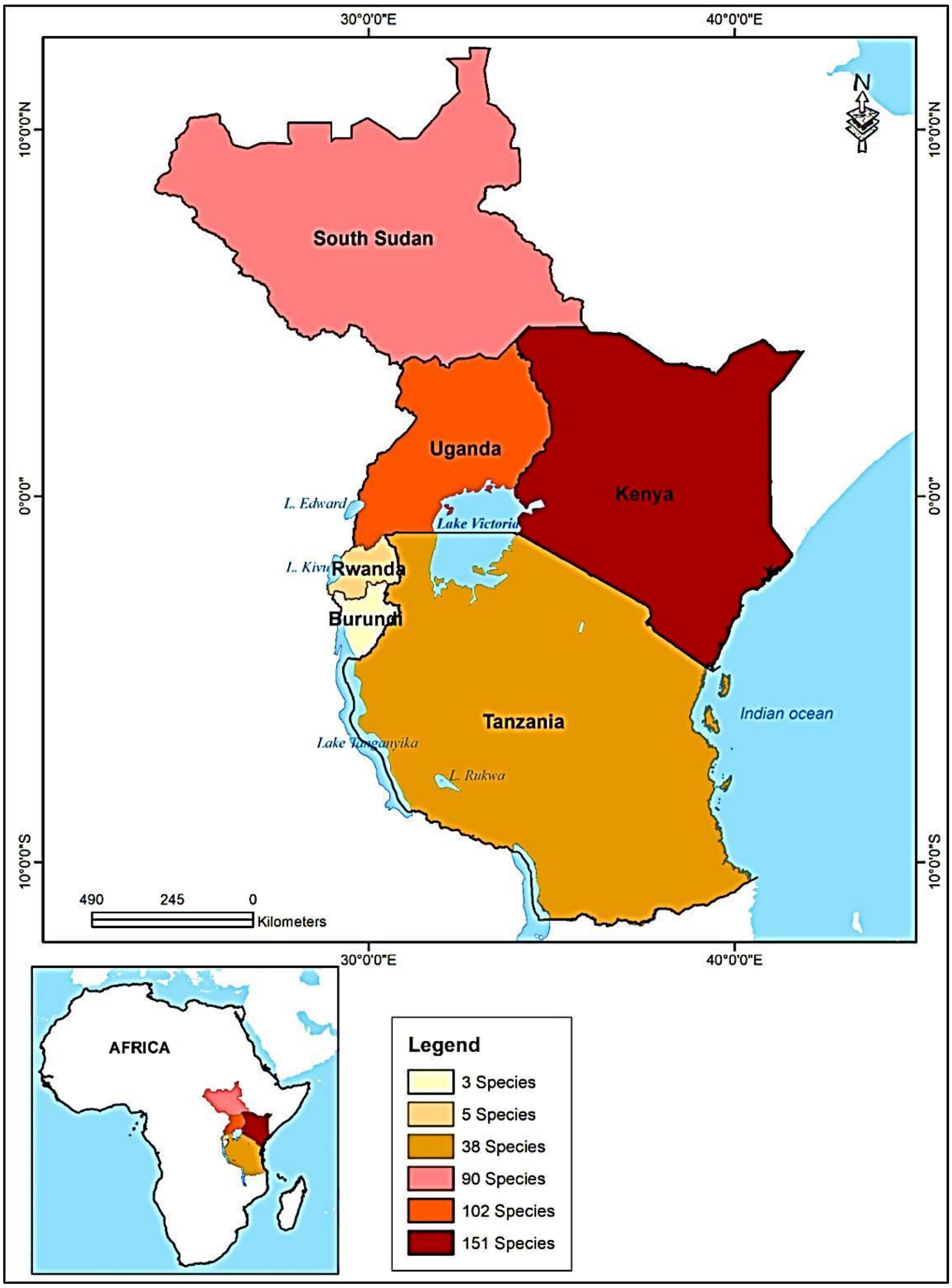

Figure 3:
Distribution of arbovirus vector mosquito species across East African Countries described between 1940-2020

Table1:
The proportion of mosquito Arbovirus vectors species in East Africa (1940-2020)

Country	**No of studies**	**No of species**	**(%)**	**Mosquito genera (%)**					
				Aedes	T. spp	Culex	Anopheles	Cq. spp	Other genera
TANZANIA	21	38	9.8	9.5	15.8	10.9	8.3	6.5	8.6
KENYA	47	151	38.8	39.4	26.3	36.1	43.8	45.2	40.0
UGANDA	45	102	26.2	26.3	42.1	19.3	16.7	48.4	34.3
SUDAN	11	90	23.1	22.6	15.8	33.6	20.8	0.0	17.1
RWANDA	1	5	1.3	2.2	0.0	0.0	4.2	0.0	0.0
BURUNDI	1	3	0.77	0	0.0	0.0	6.3	0.0	0.0
TOTAL	**126**	**389**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Key: T. spp-Taeniorhynchus species; Cq = Coquillettidia species

In Kenya, Henderson *et al* [43] reported natural infection by Semliki virus in *An. funestus*, NDUV was also isolated from *Aedomyia furfurea* in Tana delta [42] and *Cq. Fuscopennata* in Busia [23]. Nevertheless, many arboviruses have been isolated from Aedes and Culex mosquitoes as indicated in Table 2.

Table 2:
The distribution of mosquito species found naturally infected with viruses in East Africa (1940-2020)

Genera	**Species**	**Virus incriminated**	**Location/Country in East Africa**	**References**
Aedes	*Ae. simpsoni*	YFV, NTAV	Bwamba, Ntaya,UGANDA, Rabai,Nairobi, kerio-KENYA	[29, 38, 47]
	Ae. africanus	ZIKV, YF,RVF, CHIKV, NTAV, DENV	Zika,Semliki, Ntaya, Lunyo forests-UGANDA, Karagwe, Sengerema-TANZANIA, Kericho, Rift valley province-KENYA	[22, 25-28, 30-32, 47, 50]
	Ae. aegypti	CxFV, ISFVs, DENV, YF, RVFV,CHIKV,	Kwale, Baringo, Busia, Kakamega, Kilifi, Rabai, KENYA, Khartoum, SUDAN, Karagwe, Kyerwa,Kyela, Kajujumule, Sengerema, Dar es Salaam-TANZANIA	[3, 14, 32, 36-38, 44, 50, 51]
	Ae. dentatus	Pongola virus, flavivirus orthobunyavirus	Masarbit mountain, Central,KENYA	[13, 43]

		es		
	Ae. lineatopennis	RVF	KENYA	[49]
	Ae. cumminsii	RVF	KENYA	[49]
	Ae. keniensis	YF	Kerio valley, Rift Valley provice-KENYA	[30]
	Ae. apicoargenteus	ZIKV, NTAV	Zika forest, Ntaya-UGANDA	[26, 47]
	Ae. mcintoshi	BUNV, Pongola, Ngari viruses, NDUV, SFV BBKV, USUV, RVFV, CFAV	Garissa, Ruiru, Thika district-KENYA	[23, 39, 41, 48, 52]
	Ae. ochraceous	NDUV, BBKV, USUV	Kilifi, Kirinyaga,Garissa-KENYA	[23, 40, 41, 48]
	Ae. tricholabis	NDUV	Garissa-KENYA	[23]
	Ae. sudanensis	NDUV, BBKV, SFV,WNV	Garissa, Tana River-KENYA	[40, 42]
	Ae. pembaensis	RVFV	Kilifi, Kirinyaga, Baringo-KENYA	[48]
	Ae. tarsalis	Pongola virus	Luwawa Forest-UGANDA	[12]
	Ae. albomarginatus	NTAV	Ntaya-UGANDA	[47]
	Ae. longipalpis	UGANDA virus, CxFV	UGANDA, Kwale, Kakamega, Busia-KENYA	[36, 53]
	Ae. ingrami	UGANDA virus	UGANDA	[53]
	Ae. natronius	UGANDA virus	UGANDA	[53]
	Mansonia uniformis	RVFV, ONNV, NDUV	Garissa, Baringo-KENYA, Bubaale-UGANDA	[33, 40, 41, 48]
Coquillettidia	*Cq. fuscopennata*	SINV, Pongola virus	Busia-KENYA, Luwawa Forest-UGANDA	(16, 23)
	Cq. metallica			[12]
	Mansonia Africana	Mburo virus Pongola virus, Mburo virus	Lake Mburo NP-UGANDA Masarbit mountain, KENYA Lake Mburo NP, Entebbe,	[12, 43, 46, 48]
Aedomyia		RVFV, SINV,	Lugazi- UGANDA	
	Aedomyia furfurea	CxFV, NAKV NDUV	Tana River-KENYA	[42]
Culex	*Cx. zombaensis*	Pongola virus, RVF	Masarbit mountain, KENYA	[43, 49]
	Cx. antennatus	RVF, Arumowot virus; USUV	KENYA, Jinja, Kakira Sugar-UGANDA	[12, 49]
	Cx. vansomerini	RVF,NDUV, flavivirus orthobunyaviruses	Tana River, KENYA	[13, 42, 49]
	Cx. univittatus	WNV, RVFV, Arumowot virus;	Turkana, KENYA Jinja, Kakira Sugar-	[12, 14, 23, 35, 36, 48]

		USUV, CxFV, BUNV	UGANDA Kakamega, Busia,Baringo and Mombasa -KENYA	
	Cx. rubinotus	NDUV, Witwatersrand,	Marigat-KENYA, UGANDA	[12, 23]
	Cx. pipiens	Germiston viruses USUV, NDUV, BUNV, RVFV	Tana River, Baringo, Kisumu-KENYA Khartoum, West Nile-SUDAN	[14, 23, 42, 44]
	Cx. bitaeniorhynchus	NDUV, RVFV	Kilifi,Garissa, Tana River-KENYA,	[42, 48]
	Cx. poicilipes	RVFV, Ntaya Virus	KENYA, Ntaya-UGANDA, White Nile and Khartoum,SUDAN	[44, 47, 48]
	Cx. quinquefasciatus	RVFV, SINV, CxFV,WNV, CxFV, NAKV	Garissa, Kakamega, Busia, Ijara-KENYA Entebbe-UGANDA	[36, 40, 45, 46, 48]
	Cx. neavei	WNV, SINV	Queen Elizabeth, Lake Mburo NPs-UGANDA,	[12]
	Cx. perfuscus	BBKV, Mossuril Kamese viruses	Semliki NP- UGANDA,	[12]
	Cx. pruina,	NTAV	Ntaya-UGANDA	[47]
	Cx. moucheti	NTAV	Ntaya-UGANDA	[47]
Anopheles	*An. funestus*	Semlinki virus, ONNV Ngari Virus, BUNV, BWAV, Nyando virus, CxFV, flavivirus, orthobunyaviruses	Masarbit mountain-KENYA, UGANDA Kisumu,Tana-delta, Central,KENYA Bubaale- central UGANDA Busia, Kakamega and Mombasa-KENYA	[13, 21, 23, 33, 34, 36, 43]
	An. christyi	RVF	KENYA	[49]
	An. pharoensi	RVF	KENYA	[49]
	An. gambiae	ONNV, CxFV, BUNV, RVFV	Busia, Kakamega and Mombasa-KENYA, Baringo-KENYA, UGANDA,White Nile and Khartoum-SUDAN	[14, 21, 34, 36, 44]
	An. squamosus	RVFV	KENYA	[48]
	An. arabiensis	RVFV	UGANDA,White Nile and Khartoum-SUDAN	[44]
	An. coustani	RVFV	UGANDA,White Nile and Khartoum-SUDAN	[44]
Taeniorhynchus	*Taeniorhynchus pseudoconopas*	NTAV	Ntaya-UGANDA	[47]
	Uronataenia	NTAV	Ntaya-UGANDA	[47]

alboabdominalis			
Theobaldia fraseri	NTAV	Ntaya-UGANDA	[47]
T. aurites	NTAV	Ntaya-UGANDA	[47]

Key: Ntaya virus (NTAV), Bunyamwera virus (BUNV), Bwamba virus (BWAV), Rift Valley fever virus (RVFV), UGANDA S virus (UGSV), Dengue virus (DENV), Usutu virus (USUV), Yellow fever virus (YFV), West Nile virus (WNV), Zika virus (ZIKV), Babanki virus (BBKV), Chikungunya virus (CHIKV), Ndumu virus (NDUV), Semliki Forest virus (SFV), O'nyong-nyong virus (ONNV), Sindbis virus (SINV), Culex flavivirus (CxFV), Nakiwogo virus (NAKV), Cell fusing agent virus (CFAV), insect-specific Aedes flaviviruses flavivirus (ISFVs)

Vector distribution

Information on vector distribution is presented in tables 2-4. Several studies indicate common species with a cosmopolitan distribution in the region. Most species in the Aedes genera such as *Ae. africanus, Ae. dendrophilus, Ae. tarsalis, Ae. circumluteolus, Ae. aegypti, Ae. lineatopennis, Ae. mediopunctutus, Ae. sudanensis, Ae. mcintoshi, Ae. dentatus, Ae. bromeliae, Ae. metallicus, Ae. durbanensis, Ae. apicoargenteus, Ae. ingrami, Ae. nigerrimus, Ae. vittatus, Ae. scatophagoides Ae. simpsoni* and many other species indicated in Table 3 have been documented in almost every country in East Africa with exception of Rwanda and Burundi [43, 49, 50, 54-59]. Similarly, species in Culex genera such as *Cx. zombaensis, Cx. nebulosus, Cx. antennatus, Cx. tigripes, Cx. annulioris, Cx. cinereus, Cx. theileri, Cx. poicilipes, Cx. univittatus, Cx. macfiei, Cx. quinquefasciatus, Cx. ethiopicus, Cx. duttoni, Cx. decens* are the common species in Tanzania, Kenya, Uganda and Sudan [12, 50, 60-67]. However, some species have limited distribution and are endemic in certain countries. *Ae. Ruwenzori* has been documented once from the spur of Ruwenzori in Uganda but its role in the transmission of arboviruses has not been established since its identification in the 1950s [68]. Similarly, several studies [13, 23, 66, 69-73] report the distribution of the following species *Aedomyia furfurea, Ae. embuensis, Ae. ochraceous, Ae. tricholabis, Ae. unidentatus, Ae. calignosus, Ae. subdentatus* and *Ae. durbanensis, Ae. chaussieri, Ae. heischi* and *Ae. calceatus* in Kenya, but the information on the occurrence of these species in other countries in East Africa is not available. Furthermore, *Ae. stenoscutus, Ae. stokes, Ae. natronius, Ae. adersi, Ae. fraseri, Ae. abnormalis* have limited distribution and were detected once in Uganda during the 1950s [27, 74]. In addition, *Ae. caspius* and *Ae. caballus* have been documented only in Sudan [75, 76] whereas, *Ae. albicosta* has only been documented in Tanzania the by then Tanganyika [77], *Ae. neoafricanus* and *Ae. opock* species have been only recorded in Rwanda [78]. Generally speaking, the literature on arbovirus vectors in Rwanda and Burundi is scanty.

Table 3:
The distribution of arbovirus vector species from Aedes and Aedomyia genera in East Africa (1940-2020)

Species	Location/Country in East Africa	References
Ae. simpsoni	Bwamba, Acholi, Ntaya,Mpigi, Bwayisa, Bukedi- UGANDA, Kidatu, Karagwe, Kyerwa, Kilombero, Ulanga, Sengerema, Dar es Salaam-TANZANIA,SUDAN,Taita-Taveta, Kakamega, Kisumu, Rabai, Kerio, Central province-KENYA,	[3, 29, 46, 47, 54-56, 60, 64, 68, 71, 79-90]
Ae. africanus	Bwamba, Lunyo, Zika and UGANDA forests, Acholi, Teso, Bukedi, Ntaya-UGANDA; Kerio,Baringo, Kakamega, Rift valley province-KENYA; Karagwe, Kyerwa, Kilombero, Ulanga, Sengerema –TANZANIA; SUDAN, RWANDA	[22, 25, 28-31, 47, 51, 53, 55, 56, 58, 75, 84, 86, 91-93]
Ae. dendrophilus	UGANDA; Kidatu-TANZANIA	[78, 89]
Ae. tarsalis	Baringo, Mombasa, Faza, Kilifi, Garissa, Lamu, Nairobi-KENYA; Bwamba, Zika forest, Northerneast- UGANDA,	[12, 53, 64, 67, 69-71, 82, 94]
Ae. ruwenzori	Kakuka, Bunguha and Kizimba-UGANDA;	[65]
Ae. circumluteolus	Mpigi, Zika forest, Westen and Northeastern, UGANDA-UGANDA; Kilifi, Kirinyaga, Baringo, Garissa, Kiu River, Ruiru, Thika District, Central Province, Uasin, Garissa, Sukari ranch, Gishu, Rift Valley province -KENYA; Darfur-SUDAN;	[39, 48, 53, 54, 61, 63, 64, 77, 82, 90, 95-98]
Ae. embuensis	Northern districts-KENYA	[43]
Ae. aegypti	Malindi, Kilifi, Bura, Kakamega,Tana River, Mombasa, Nairobi, Kisumu, taita-Taveta, Kacheliba, West Pokot county, Kwale, Busia,Northern districts-KENYA; Zika forest-UGANDA;Dar es Salaam, Ngorongoro, Kidatu, Moshi,Ifakara, Karagwe, Kyerwa, Kilombero, Ulanga, Sengerema -TANZANIA; Nuba mountains, White Nile, Khartoum, Port SUDAN city,Darfur-SUDAN; Northeastern and western UGANDA, Semliki forest, Mpigi-UGANDA;RWANDA	[3, 20, 23, 32, 36, 43, 44, 52, 54-56, 59, 60, 64, 67, 68, 72, 75, 83, 86, 89, 90, 93, 96, 97, 99-117]
Ae. keniensis	Nothern districts of KENYA, south Kerio Valley, Rift Valley Province, Kakamega, Kisumu-KENYA	[30, 43, 86, 88]
Ae. ngong van Someren	Nothern districts of KENYA	[43]
Ae. aegypti formosus	KENYA; Zika forest-UGANDA	[53, 93, 97, 99, 104]
Ae. furcifer	SUDAN, Bwamba-UGANDA;Baringo-KENYA	[14, 61, 71, 125]
Ae. caspius	Khartoum State,Port SUDAN City -SUDAN;	[73]
Ae. caballus	Khartoum State-SUDAN	[73]

Ae. unidentatus	Uasin,Gishu, Rift Valley province-KENYA	
Ae. calignosus	Uasin,Gishu, Rift Valley province-KENYA	[63]
Ae. subdentatus	Uasin,Gishu, Rift Valley province-KENYA	[63]
Ae. albothorax	Northwestern-UGANDA; Mombasa, Faza-KENYA;Tanganyika	[63]
Ae. chaussieri	Central,KENYA	[64, 70, 74]
Ae. heischi	Mombasa, Faza –KENYA	
Ae. calceatus	Mombasa, Faza –KENYA	
		[13]
Ae. albicosta	Tanganyika	[70]
Ae. neoafricanus	RWANDA	[70]
Ae. opock	RWANDA	
Ae. natalensis	Kisumu-KENYA; Kyela, Kajunjumele, Njisi-TANZANIA	[74]
Ae. grahami		[75]
Aedomyia africana	Northwestern, UGANDA	[75]
Ae. vexans	SUDAN; Baringo-KENYA	[32, 88]
Ae. calceatus	White Nile, Khartoum State-SUDAN	[64]
	Mombasa, Faza-KENYA	[61, 94]
		[44, 73]
		[70]

Discussion

Studies in this review mainly present information on vector species composition, diversity and distribution (71%), only 36 (29%) studies focused on transmission dynamics of YF, RVF, Zika, DENV or CHIK viruses in East Africa. There was an increasing trend of entomological studies between the years 1940-1950 (Figure 1), many studies during that particular time were conducted in Uganda following the YF outbreak [29, 31, 55, 79, 80]. During that time, other viruses such as Zika, Ntaya and Uganda were also isolated from vector mosquitoes [25, 28, 47, 53]. Entomological studies decreased from 17 articles in 1960 to 4 articles in 1970 during which there were no records of arboviral epidemics, this observation suggests that many studies are conducted during epidemics and the interepidemic studies are generally few. Nevertheless, other arboviruses such as Semlinki, Pongola, Chikungunya and O'nyong-nyong were also encountered in mosquito vectors during that time [21, 22, 34, 43]. The trend further indicates that studies remained generally few between the years 1970- 2000, however, viruses continued to emerge although many didn't lead to arboviral infection outbreaks in the region except for the RVFV epidemic in 1998/1999 following El-Nino rainfalls. Arboviruses are continuously emerging even during interepidemics, in 1985 Linthicum *et al*. isolated RVFV from a range of mosquito vector species: *Aedes lineatopennis, A. cumminsii, Culex antennatus, Culex vansomerini, Culex. zombaensis, An. christyi*, and *An. pharoensi* in Kenya [49] and the virus has remained in circulation in various East African countries causing epidemics from time to time [41, 48]. In White Nile and Khartoum states in Sudan, RVFV was isolated from *An. arabiensis, An. coustani, Cx. pipiens, Cx. poicilipes* and *Ae. aegypti* [44]. It is interesting to note that RVFV can be vectored by mosquitoes from various genera that are available within the region. Other viruses such as Bwamba and Nyando were also isolated from *An. funestus* mosquitoes in 1999 in Uganda [33] and West Nile virus was detected from *Cu. univittatus* in Rift Valley Province in Kenya [13]. Between the years 2000-2010, entomological studies picked up reaching 13 articles in 2010. Similarly, many arboviruses were also detected from vector mosquitoes including BUNV, BBKV, NDUV and SINV from Aedes, Mansonia and Culex mosquitoes [14, 40]. From 2010-2020, the trend indicates a steep increase in entomological studies, a total of 53 studies included in this review were conducted during this particular time. These studies coincided with the DENV epidemics occurring in the region [3, 37, 50, 51]. Moreover, other arboviruses are increasingly detected from various parts of East Africa including Usutu, Ngari, Kamese, Witwatersrand, Germiston, Mburo, Arumowot, CxFV and CFAV all vectored by multiple mosquito vectors including, *Cq. fuscopennata* [12, 23, 36, 39]. The ability of vector mosquitoes to host a range of arboviruses is of public health concern and suggests that these vectors are responsible for the maintenance of viruses in circulation. Furthermore, arboviruses have been detected from male mosquitoes, and West Nile and RVF viruses were detected from males of *Cu. univittatus* and *Aedes sudanensis* respectively in Kenya [35, 42]. This indicates the role of male mosquitoes in the epidemiology of arboviral infections and suggests that interventions targeting non-host-seeking mosquitoes are important to complement the existing ones. Although virus detection and or isolation from a wild population of mosquitoes does not necessarily translate to virus transmission, it lends support to evidence from laboratory studies and is also important to assess the relative importance of competent vector species in disease maintenance and/or transmission.

Table 4:
The distribution of arbovirus vectors from Culex genera in East Africa (1940-2020)

Species	Location/Country in East Africa	References
Cx. zombaensis	Thika, Kizigo, Nyali, Uasin,Gishu, Rift Valley province, Baringo, Northern and central	[13, 14, 23, 43, 62, 63, 76, 98, 118]
Cx. nebulosus	districts-KENYA; SUDAN;	
	Kisumu, Northern districts-KENYA;	[43, 54, 58, 62, 64, 88, 89, 96]
Cx. antennatus	Northwestern UGANDA, Zika forest-UGANDA; Darfur-SUDAN; Kidatu-TANZANIA	[12, 39, 49, 54, 57, 61-64, 88, 97, 98, 118]
Cx. tigripes	Ngorongoro-TANZANIA; Diani Karen, Karura, Kakamega, Sukari Ranch ,Naivasha, Uasin,Gishu, Rift Valley province, Sukari ranch, Thika-KENYA;	[14, 39, 54, 56, 57, 59-63, 69, 88, 96, 97, 118]
Cx. annulioris	SUDAN;Western UGANDA; Karagwe, Kyerwa, Kilombero, Ulanga, Sengerema, Ngorongoro-TANZANIA; Bura, Tana river, Thika, Uasin,Gishu, Rift Valley province, Garrisa, Lamu, Baringo, Kisumu-	[13, 14, 39, 57-60, 63, 64, 68, 88, 90, 94, 96, 97]
Cx. cinereus	KENYA; Darfur-SUDAN; Western UGANDA; Ngorongoro-TANZANIA; Northwestern UGANDA, Mpigi, Zika forest-UGANDA;Taita-Taveta, Bura, Tana river, Kisumu, Uasin,Gishu,	[54, 57]
Cx. theileri	Baringo, Rift Valley province-KENYA; Darfur-SUDAN	
Cx. vansomerini	Ngorongoro-TANZANIA;SUDAN;	[36, 54, 62, 64, 84, 88, 90]

	Nothwestern Uganda, Acholi, Teso, Bukedi,	
Cx. moucheti	Mpigi -UGANDA; Central Nyanza Province,	
Cx. insignis	Kwale, Kakamega, Busia, Mombasa, Kisumu-	
Cx. poicilipes	KENYA	[14, 62, 63, 118]
	Thika, Uasin,Gishu, Rift Valley province -	[49, 63]
	KENYA; SUDAN;	
	Diani Karen, Karura, Kakamega, Sukari	[47, 58, 62]
Cx. univittatus	Ranch ,Naivasha, Uasin,Gishu, Rift Valley	[58]
	province -KENYA	[44, 47, 48, 54, 58-60,
	Zika forest, Ntaya-UGANDA; SUDAN;	63, 64, 68, 71, 90, 96]
Cx. macfiei	Zika forest-UGANDA	
Cx. quinquefasciatus	Zika forest, Ntaya, Bwamba, Mpigi,	
	Northwestern-UGANDA; Darfur, White Nile,	
	Khartoum -SUDAN; Taita-Taveta, Kilifi,	[35, 42, 48, 58, 61, 63,
	Kirinyaga, Bura, Baringo, Uasin,Gishu,	64, 68, 88, 96]
	Baringo, Rift Valley province, Garissa-KENYA	
Cx. ethiopicus	Zika forest, Northwestern-UGANDA; Taita-	[54, 94]
Cx. duttoni	Taveta, Kilifi, Kirinyaga, Baringo, Garissa,	
	kisumu, Uasin,Gishu, Rift Valley province Tana	[19, 36, 40, 45, 46, 48,
Cx. decens	River-KENYA; Darfur-SUDAN;	56, 59, 64, 68, 72, 90,
	SUDAN; Baringo -KENYA	101]
Cx. perfuscus	Taita-Taveta, Kilifi, Kirinyaga, Baringo, Busia,	
Cx. perfidiousus	Kwale, Kakamega, Garissa, Ijara, Malindi-	
Cx. weschei	KENYA; Mara River-TANZANIA&KENYA;	
Cx. culicioma	Port Sudan City-SUDAN; Entebbe, Lugazi,	[54, 60-62, 94, 96]
Cx. fuscocephala	Mpigi, Northwestern-UGANDA; Karagwe	[14, 54, 56, 61, 62, 88,
Cx. bitaeniorhynchus	Kyerwa Kilombero Ulanga Sengerema-	96]
	TANZANIA	
Cx. arbieeni	Darfur-SUDAN;Tana river Kisumu,Baringo-	[36, 54, 61, 90, 96, 97]
Cx. pusillus	KENYA;	
Cx. salisburiensi	Darfur-SUDAN; Karagwe, Kyerwa, Kilombero,	
Cx. sitiens	Ulanga, Sengerema-TANZANIA	[12, 54, 61, 62, 64, 96]
	Darfur-SUDAN; Mpigi,Northwestern Uganda-	[54]
Cx. argenteopunctatus	UGANDA; Kwale, Kakamega, Busia and	[54, 62]
Cx. simpsoni	Mombasa -KENYA	[68]
	Darfur-SUDAN; Northwestern -UGANDA;	[68]
Cx. sinaiticus	SUDAN	[13, 42, 48, 60, 62, 63,
Cx. laticinctus	SUDAN	69]
	Taita-Taveta, KENYA	
Cx. fatigans	Taita-Taveta, KENYA	[54, 96]
Cx. toroensis	SUDAN; Uasin,Gishu, Rift Valley province,	[62]
Cx. invidiosus	Lamu, Tana River, Kilifi, Kirinyaga, Baringo,	[62, 96]
Cx. trifoliatus	Garissa -KENYA;	[62, 63, 72]
Cx. guiarti	Darfur-SUDAN	
Cx. ingrami	SUDAN	[62]
Cx. grahami	Darfur-SUDAN	[14, 36, 62, 88]
Cx. pruina	Port Sudan City –SUDAN; Uasin,Gishu, Rift	
Cx. musarum	Valley province, KENYA	[54, 61, 62, 96]
Cx. rubinotus	SUDAN	[36, 62, 96]

Cx. hancocki	SUDAN; Kwale, Kakamega, Busia,	
Cx. ventrilloni	Mombasa,Baringo, Kisumu-KENYA	[61, 62, 74, 88]
Cx. mirificus	Darfur; SUDAN	[62, 63]
Cx. aurantapex	Darfur; SUDAN; Kwale, Kakamega, Busia and	[62, 90]
Cx. jinjaensis	Mombasa -KENYA	[62]
Cx. hopkinsi	SUDAN; Kisumu-KENYA;TANGANYIKA	[62, 63]
Cx. neavei	SUDAN; Uasin, Gishu, Rift Valley province-	[62, 88]
Cx. pipiens	KENYA	[96]
Cx. adersianus	SUDAN;Mpigi-UGANDA	[47, 62]
Cx. rima	SUDAN	[87]
Cx. watti	SUDAN; Uasin,Gishu, Rift Valley province-	[12, 98]
	KENYA	[88]
Cx. eretmapodites	SUDAN;Kisumu-KENYA	[63]
	Darfur-SUDAN	[63]
Cx. uranotaeniahenrardi	SUDAN;Ntaya-UGANDA	[63]
	UGANDA	[63]
Cx. chrysogaster	UGANDA; KENYA	[63]
Cx. horridus	Kisumu- KENYA	[54]
Cx. Kingianus	Uasin,Gishu, Rift Valley province-KENYA	[12, 14, 54, 61]
Cx. insigns	Uasin,Gishu, Rift Valley province-KENYA	[19, 23, 42, 44, 56, 57,
Cx. aurites	Uasin,Gishu, Rift Valley province-KENYA	59-62, 64, 90, 94, 96,
Cx. cinerellus	Uasin,Gishu, Rift Valley province-KENYA	102, 105, 106, 118]
Cx. striatipes	Uasin,Gishu, Rift Valley province-KENYA	[64]
	SUDAN; UGANDA;Baringo-KENYA	[14]
	Ngorongoro, Karagwe, Kyerwa, Kilombero,	
	Ulanga, Sengerema -TANZANIA; Kilifi,	
	Mombasa,Bura, Baringo,Tana River, Thika –	[56]
	KENYA; White Nile, Khartoum Darfur;	[56]
	SUDAN; Mara River-KENYA&TANZANIA;	[53, 64, 93]
	Mpigi, Northwestern, UGANDA	[53, 64, 93]
	Baringo-Kenya	[53, 64, 93]
	Karagwe, Kyerwa, Kilombero, Ulanga,	[53]
	Sengerema -TANZANIA	[53, 64, 93]
	Karagwe, Kyerwa, Kilombero, Ulanga,	[53, 93]
	Sengerema –TANZANIA	[14]
	Zika forest, Northwestern, - UGANDA	
	Baringo-KENYA	

Our review indicates an increasing number of mosquito vector species over the years in the East African region. Mosquitoes in the Aedes and Culex genera are the most diverse groups and known vectors of arboviruses [81, 82]. The availability of these vectors in the East African region is of public health concern given the similarity in climate, habitats and ecological settings of the countries that may permit the exchange of the viruses among member states leading to regional epidemics. The diversity of arbovirus vectors is very high in Kenya, followed by Uganda and Sudan (Figure 2), going forward by the current trend, increasing arboviral infection outbreaks are foreseeable in future. The diversity of mosquito vector species described in East Africa gives an enormous choice to arboviruses to infect vector species thereby increasing the potential of spread. The ability of vector mosquitoes to adopt from slyvatic zoophilic cycles to urban or peridomestic transmission cycles further indicates that arboviruses will continue to emerge and future epidemics should be expected. It was also interesting to note that some species were only encountered once for a period of 60 years and some species appeared to be endemic in specific countries. For example, species such as *Ae. ruwenzori*, *Aedomyia furfurea, Ae. embuensis, Ae. ochraceous, Ae. tricholabis, Ae. unidentatus, Ae. calignosus*, *Ae. subdentatus* and *Ae. durbanensis*, *Ae. chaussieri, Ae. heischi* and *Ae. calceatus*, *Ae. stenoscutus, Ae. stokes, Ae. natronius*, *Ae. adersi, Ae. fraseri, Ae. abnormalis Ae. albicosta Ae. neoafricanus and Ae. opock* have been described with limited distribution in specific countries in East Africa [13, 23, 42, 66, 71, 73, 75-78, 83]. Some of these species were only reported once, this indicates that either, the species were accidentally introduced into the region or the environment could not support their breeding and proliferation and they have disappeared. Nonetheless, the role of these rare species in the transmission and maintenance of arboviruses in the region has not been established.

Risk factors responsible for the emergence of arboviruses

Despite the investment made over the years in the control of arboviruses and other vector-borne diseases, we still face the prospect of emerging or reemerging arboviruses. Most arboviruses originate from wildlife in their sylvatic reservoirs and disperse globally. The expansion of the arboviruses among other factors is attributed to anthropological behaviours such as land use and habitat fragmentation, unregulated marketing of domestic and wild animals, urbanization and expanding human population densities, increasing human mobility, and dispersion of livestock, arthropods and commercial goods via expanding transportation systems [84]. The rapidly expanding cities in East Africa which are unplanned coupled with expanding human population enhance the creation of mosquitogenic environments that favour the proliferation of arbovirus vectors such as *Ae. aegypti* [16]. The high human population in these cities further provides blood meals for vector mosquitoes and facilitates interhuman transmission of arboviruses. Previous studies in Kenya and Tanzania indicated that *Ae. aegypti* breeds in water storage containers in most towns [3, 51, 85, 86] this is attributed to a lack of piped water that necessitates the storage of water in containers providing breeding grounds for arbovirus vectors. Climatic conditions in East African countries like in many other tropical countries support the breeding and growth of vector mosquitoes. Countries in East Africa are characterized by distinct dry and rainy seasons, the rainy season span from March to June each year resulting in increasing aquatic habitats for mosquito breeding, therefore, increasing the risk of arbovirus transmission. Mweya *et al*. [87] predicted the increase in average annual temperatures from 1 to 3°C above the baseline, increase in precipitations, and intensification of extreme events such as floods make suitable conditions for the breeding of flood water mosquitoes. Deteriorating infrastructure, poor access to health, water and sanitation services, habitat fragmentation and widespread poverty contribute to conditions that modify the environment, which directly influences the risk of disease within the urban and peri-urban ecosystem[88]. The rapid increasing human population density in fragmented habitats coupled with increasingly adaptable anthropophilic behaviour of Aedes (Stegomyia) vectors pose an additional risk of zoonotic arboviruses such as YF, RVF and WNE [89]. The Slave trade is envisaged for the spread and expansion of arboviruses fueled by increasing international travel that introduced vectors or mosquito eggs infected with arboviruses into new areas [90, 91]. The risk of emerging and re-emerging arboviral diseases is on the increase and their geographical distribution is expanding globally but the actual estimate of circulating arboviruses in the region is largely underestimated. This is due to a lack of continuous and reliable regional or country-wide vector surveillance and reporting systems on arboviruses vectors.

Conclusion

The implications of this systematic review are clear, arbovirus vectors are diverse in East Africa and are likely to continue spreading because the conditions are favourable, and their potential role in the transmission of arboviruses should remain a concern for public health officials. The interepidemic entomological studies are few but indicate the active continuous circulation of viruses in the region therefore future epidemics should be expected. Studies on arbovirus vectors are generally few in Rwanda and Burundi, given the interaction with other countries and similarities in climatic conditions the likelihood of virus exchange is high, and a regional vector surveillance system is an urgent need.

Competing interests

The authors declare they have no competing interests

Author contributions

AP, SM and SLL conceived and designed the search strategy and the review. AP and SLL independently performed the search, screened titles, abstracts and full texts, and applied inclusion and exclusion criteria. AP, SM and SLL performed data extraction, quality appraisal, checked data extraction and interpreted the data. AP drafted the manuscript and all authors revised the manuscript.

Acknowledgement

This review was supported by the Consortium for Advanced Research Training in Africa (CARTA). CARTA is jointly led by the African Population and Health Research Center and the University of the Witwatersrand and funded by the Carnegie Corporation of New York (Grant No. G-16-54067), Sida (Grant No:54100113), the DELTAS Africa Initiative (Grant No: 107768/Z/15/Z). The DELTAS Africa Initiative is an independent funding scheme of the African Academy of Sciences (AAS)'s Alliance for Accelerating Excellence in Science in Africa (AESA) and supported by the New Partnership for Africa's Development Planning and Coordinating Agency (NEPAD Agency) with funding from the Wellcome Trust (UK) and the UK government. The statements made and views expressed are solely the responsibility of the authors.

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