



Review

Understanding key vectors and vector-borne diseases associated with freshwater ecosystem across Africa: Implications for public health



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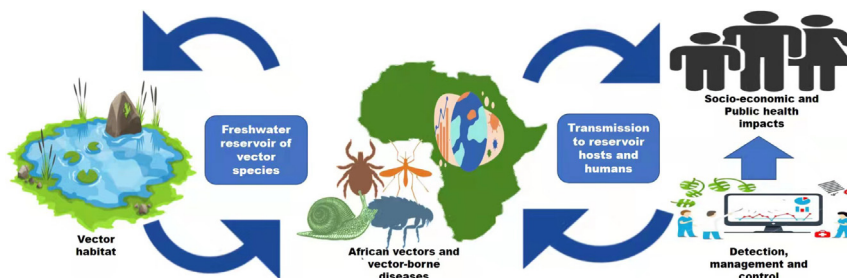
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HIGHLIGHTS

- Populations and abundance of freshwater organisms are increasing in Africa.
- Africa bears a disproportionately large burden of vector-borne diseases.
- Environmental changes exacerbate the abundance and disease-transmitting capacity of vectors.
- Public health programs require the inclusion of vector and habitat ecology framework.

GRAPHICAL ABSTRACT



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ABSTRACT

The emerging and re-emerging vector-borne diseases transmitted by key freshwater organisms have remained a global concern. As one of the leading biodiversity hotspots, the African ecoregion is suggested to harbour the highest number of freshwater organisms globally. Among the commonly found organisms in the African ecoregion are mosquitoes and snails, with a majority of their life cycle in freshwater, and these freshwater organisms can transmit diseases or serve as carriers of devastating diseases of public health concerns. However, synthetic studies to link the evident abundant presence and wide distribution of these vectors across the freshwater ecosystems in Africa with the increasing emerging and re-emerging vector-borne diseases in Africa are still limited. Here, we reviewed documented evidence on vector-borne diseases and their transmission pathways in Africa to reduce the knowledge gap on the factors influencing the increasing emerging and re-emerging vector-borne diseases across Africa. We found the population distributions or abundance of these freshwater organisms to be increasing, which is directly associated with the increasing emerging and re-emerging vector-borne diseases across Africa. Furthermore, we found that although the current changing environmental conditions in Africa affect the habitats of these freshwater organisms, current changing environmental conditions may not be suppressing the population distributions or abundance of these freshwater

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organisms. Instead, we found that these freshwater organisms are extending their geographic ranges across Africa, which may have significant public health implications in Africa. Thus, our study demonstrates the need for future studies to integrate the environmental conditions of vectors' habitats to understand if these environmental conditions directly or indirectly influence the vectorial capacities and transmission abilities of vectors of diseases. We propose that such studies will be necessary to guide policymakers in making informed policies to help control vector-borne diseases.

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1. Introduction

The African continent is suggested to have the highest number of freshwater ecoregions globally (Abell et al., 2008). Ecologically, the freshwater ecoregions are mainly used to describe watersheds or segments of larger basins situated within a geographically distinct cluster of natural communities (see; Thieme et al., 2006). The freshwaters of Africa are incredibly diverse, with earlier studies categorising them into 90 freshwater ecoregions, including associated islands in Africa (Thieme et al., 2006; Abell et al., 2008). Thus, the freshwater ecosystems serve many diverse communities of organisms and millions of Africans who depend on these waters for life and survival (Johnson et al., 2001). Among the organisms harboured by the freshwater ecosystem may include several organisms (e.g., some insects and snails) that could transmit diseases to humans or even serve as carriers of devastating human disease of major public concern (Chala and Torben, 2018; Brady and Hay, 2020).

The association between the African freshwater ecoregions and disease vectors could be that the freshwater provides a conducive environment for the vectors to complete all or some key stages of their life cycle (Chala and Torben, 2018). For instance, mosquitoes that are vectors of *malaria*, *lymphatic filariasis*, *dengue*, and many arboviruses have key stages of their life-cycle associated with freshwater bodies (Sundaraneedi et al., 2017; Shaw and Catteruccia, 2019). Additionally, freshwater snails that act as an intermediate host for water-borne diseases such as *schistosomiasis* are widely spread across Africa. Perhaps, the abundant presence and wide distribution of these mosquitoes and snails (serving as vectors of diseases) across the freshwater ecosystems in Africa may be responsible for the increasing public health burden of the African continent (Lehmann et al., 2021). This is because the burden of vector-borne diseases have been reported to continually extend their geographical ranges across Africa (Savić et al., 2014; Giesen et al., 2020; Lehmann et al., 2021). For instance, *malaria* and other parasitic diseases transmitted by mosquitoes or snails that inhabit freshwater are classified as important parasitic infectious diseases responsible for >400,000 deaths yearly (Bhatt et al., 2013; WHO, 2020). Also, vector-borne diseases have contributed to high poverty and poor economic development across developing African countries through medical costs and losses from productivity and tourism (Deme et al., 2017a; WHO, 2017b). This is worrying

because vector-borne diseases have continued to drop drastically across the globe (Benelli and Beier, 2017; WHO, 2017a). More concerning that, only a few studies have attempted to evaluate if the changing freshwater environments directly extend the distribution and geographical abundance of these freshwater biodiversities in the African context (Deme et al., 2017b; Lehmann et al., 2021; Okeke et al., 2022).

Interestingly, these few studies have consistently shown that previously controlled vector-borne diseases can resurge or remerge to increase the disease burden in unmanaged environments across Africa (Deme et al., 2017b; Chanda, 2020; Torto and Tchouassi, 2021). Also, the increasing water insecurity and climate change across the globe could aggravate the risks of increasing vector-borne diseases in Africa. For instance, the recent outbreak of Zika in some African countries suggests a likely expansion of the geographical ranges of *Aedes aegypti* and *Aedes albopictus* mosquitoes (Brady and Hay, 2020; Lehmann et al., 2021). If this idea is proven to be true, we would expect the effect of climate change, water insecurity, and the problem of environmental management to likely aid the vectors of these diseases to spread beyond their geographically-restricted areas (Johnson et al., 2020; Sinka et al., 2020; Lehmann et al., 2021). Thus, synthesising documented evidence on vector-borne diseases and their transmission pathways will strengthen local knowledge, support biomedical education and care-seeking pathways, and reduce the existing knowledge gaps on eliminating vector-borne diseases in Africa. Therefore, in this review study, we aim to (i) evaluate the current understanding of the burden of disease-transmitting vectors in African freshwater, (ii) synthesise established evidences on the transmission pathways and the existing surveillance of the disease-transmitting vectors across the African continent, (iii) use the current understanding of how unmanaged environments associate abundance with diversity of disease-transmitting vectors in African freshwater and, propose areas that future research are needed to expand our limited knowledge of the impact of the changing environments on the abundance and diversity of disease-transmitting vectors in African freshwater.

2. Method used for data search

The data of our review paper relied more on empirical studies with the inclusion of synthetic studies in some instances. Thus, to arrive at some of

our conclusions, we obtained the data used in this study through a thorough literature search across different search engines (e.g., Web of Science, Google Scholar, SCOPUS and PubMed). First, we used the search terms “Mosquitoes” OR “Snails” OR “Vectors” OR “Transmission” AND “Africa” OR “Dengue virus” OR “*Aedes aegypti*” AND “African ecosystem”-which were relevant to our study. Then, to further expand our search, we used the genus of vector-borne mosquitoes “*Anopheles*” OR “*Culex*” OR “*Aedes*” AND “Africa” and snails “*Bulinus*” OR “*Biomphalaria*” that have been described in Africa. We then read the abstract of papers to screen for inclusion and exclusion of studies, and went ahead to read in full studies with findings based on empirical evidence. The included empirical studies by way of in-text citations usually lead to synthetic investigative studies with insightful summaries (Sayer, 2018).

3. Major vectors in African freshwater systems

The distribution and composition patterns (abundance and species diversity) of major freshwater vectors of diseases, such as mosquitoes and snails, usually give a broader understanding of the dynamics, spread, sustenance, and potential introduction of diseases. Thus, understanding the community composition of these medically important freshwater organisms (*Anopheles*, *Culex*, *Aedes*, and snails) across Africa is what this section seeks to achieve.

Anopheles mosquitoes

Across the continent of Africa, the *Anopheles gambiae* complex and *Anopheles funestus* subgroup have recently been classified as the dominant malaria vectors (Wiebe et al., 2017); since they are almost found in most geographic and climatic regions of Africa (Deme et al., 2017b; Cornel et al., 2018; Lehmann et al., 2021). However, in addition to the major malaria vector species, studies have shown the geographical distribution of other *Anopheles* siblings that can transmit malaria across Africa (Lehmann et al., 2021). Recently, the Asian urban *Anopheles* mosquitoes (*Anopheles stephensi*) were found in some urban areas of Africa (Sinka et al., 2020). This finding suggests that the African continent might be experiencing an increasing burden of additional *Anopheles* species that were hitherto not endemic to the continent. Probably, this is a direct consequence of the highly efficient speciation characteristics of the *Anopheles* species in novel environments (Deme et al., 2017b; Cornel et al., 2018) because *Anopheles* species have shown highly efficient speciation due to increasing tolerance to challenges in modified or novel environments (Sinka et al., 2020). Thus, in addition to the endemic African *Anopheles* species, the increasing geographic range shift and highly efficient speciation of *Anopheles* mosquitoes suggest that millions across Africa are increasingly at risk of malaria infections.

Culex mosquitoes

Culex mosquito species are predominantly spread and distributed in urban areas across Africa (Deme et al., 2017b; Johnson et al., 2020; Yaro et al., 2022) due to the presence of suitable habitats, which are created by the increasingly polluted environments and the unmanaged environments (Awolola et al., 2007; Okeke et al., 2022). Notably, the *Culex* mosquito species have been found to thrive in novel (unpolluted and polluted) environments (Deme et al., 2017b; Cornel et al., 2018), and these novel environments across Africa may be supporting speciation and/or the geographic range shifts of *Culex* mosquito species (Lehmann et al., 2021). Recent studies have shown that the *Culex pipiens* complex having six subspecies (*pipiens*, *quinquefasciatus*, *pallens*, *australicus*, *globocoxitus*, and *molestus*), remained the most dominant across different environments in Africa (Johnson et al., 2020), and the *Culex quinquefasciatus* that transmit filariasis predominantly occupying urban spaces in Africa (Deme et al., 2017b; Johnson et al., 2020).

Aedes mosquitoes

Studies so far have shown that when compared to the *Culex* and *Anopheles* mosquito species, the *Aedes* mosquito species are relatively less abundant in the African continent (e.g., Deme et al., 2017a, 2017b; Cornel et al., 2018; Johnson et al., 2020; Yaro et al., 2022). However, the *Aedes*

mosquito species are still generally distributed across African countries, suggesting these the *Aedes* species are actively present and can transmit disease across the continent (Lehmann et al., 2021; Yaro et al., 2022). Furthermore, recent studies have shown that the *Aedes aegypti* and *neomelaniconus* siblings are Africa's most dominant *Aedes* mosquito species (Guarido et al., 2021). However, the *Aedes albopictus*, which was predominantly a South-east Asian mosquito species, is now found to be widely distributed across African countries (Edwards, 1920; Lehmann et al., 2021; Yaro et al., 2022). But we still have a paucity of information *Aedes* species ecology across African countries (see; Guarido et al., 2021). This is worrying, considering the increasing mosquito-borne diseases (MBDs) transmitted by the *Aedes* mosquito species across Africa and the primary roles of *Aedes* species as arboviruses disease vectors (Swei et al., 2020; Lehmann et al., 2021). Thus, more research is required to understand how *Aedes* mosquito's possible speciation impacts the emergence and re-emergence of arbovirus diseases, as recorded in recent years across Africa (WHO, 2020; also reviewed in Chala and Hamde, 2021).

Snail species

The molluscs, to which the snails belong, have at least 70,000 species (55 families) living in terrestrial or aquatic ecosystems (Rosenberg, 2014). The *Biomphalaria* and *Bulinus* genera are suggested to be the widely distributed snail species across African countries (Rabone et al., 2019). Notably, other freshwater snail genera (*Lymnaea*, *Melanoides* and *Bellamya*) snails are found in specific African freshwater ecosystems (see; Hailegebriel et al., 2022; Konan et al., 2022). Of the predominant snail genera (*Biomphalaria* and *Bulinus*), the *Biomphalaria pfeifferi* and *sudanica* subgroups and the *Bulinus truncatus* that transmit the *Schistosoma* parasite are the most successful groups of snails in Africa (Brown, 1994; Rosenberg, 2014; Konan et al., 2022), suggesting the increasing burden of schistosomiasis in Africa. This is because the presence of snail vectors primarily influences the geographic spread of schistosomiasis (Abe et al., 2018). However, we still have a paucity of information on snail species ecology across African countries, which is necessary for planning the control of schistosomiasis in Africa (McCreesh et al., 2015).

3.1. Mosquitoes as major vectors in the African ecosystems

Mosquitoes are vectors of pathogens ranging from protozoans, arboviruses, and filariae, which cause infectious diseases of public health concern, and these infectious diseases are more pronounced across Africa (Jones et al., 2013). Recently, they have been reported to transmit bacterial diseases across humans (Dieme et al., 2015). Thus, mosquitoes are increasingly becoming worrisome with their wide distribution across different eco-climatic zones of the world (Jones et al., 2013; Swei et al., 2020), with the sub-Saharan African environments having numerous mosquito species belonging to the *Anopheles*, *Culex*, and *Aedes* spreading across geographic ranges in Africa (Lehmann et al., 2021). This is due to poor environmental management policy strategies (World Health Organization, 2021; reviewed in Deme et al., 2022). Despite the numerous studies across Africa that showed how these mosquito genera widely distributed across Africa transmit diseases, little is known about how the rapidly changing climate across different eco-climatic zones will affect their abundance, composition, distribution, and infectivity rate. This lack of such studies might be a significant omission that can affect vector control and public management of diseases in the context of climate change. Because several studies have emphasized the significant role climate change will play in the host-pathogen interaction with the environment that has led to the emergence or re-emergence of various diseases (Cornel et al., 2018). Climate change, as a long-term shift in the weather conditions of an environment, may lead to extreme environmental conditions that may influence the life-cycle of insects and their role in the vector-borne infection capacity (Cornel et al., 2018; IPCC, 2022). For example, extreme environmental conditions resulting from the rapidly changing climate are suggested to significantly influence the seasonal transmission, infective capacity, and duration of mosquitoes as disease vectors (Jones et al., 2013). Presumably, climate

change will give rise to environmental conditions that directly or indirectly determine the survival, reproduction, colonisation, recolonisation, and/or persistence of mosquitoes across environments (Fig. 1). Thus, we proposed that mosquito species sorting across environments in Africa, will follow a similar pattern predicted for insect populations colonising, recolonising, and persisting in urban environments (Chown and Duffy, 2015). Notably, climate change is suggested to significantly impact the role of mosquitoes as human-vector for disease transmission (Brady et al., 2013). For instance, some studies have suggested that the public health burden of mosquito-borne disease may be susceptible to the warming scenarios that will come as a result of climate change; albeit, this remains controversial and debatable because of the lack of sufficient data to support this claim (Medlock and Leach, 2015; Guarido et al., 2021). Most studies have only focused on the occurrence rate of mosquitoes versus the intensity of their pathogens with the effect of anthropogenic climate change across different eoclimatic zones (Brady et al., 2013; Jones et al., 2013; Swei et al., 2020). However, these studies cannot exclusively implicate climatic-related factors in transmitting emerging and re-emerging pathogens by mosquitoes. Thus, the need for studies investigating how climatic-related factors directly or indirectly influence mosquitoes-borne pathogens' survival, reproduction, and transmission cannot be overemphasized. Indeed some studies have already reported that climate warming might account for 10 % of the transmission rate of mosquitoes-borne pathogens (Swei et al., 2020).

3.2. Snails as major vectors in the African freshwater ecosystems

Studies have shown that the rate at which Nematoda parasites cause diseases is directly linked with their host availability and the constant environmental changes (Chala and Hamde, 2021). Among the major widely reported organisms of public health importance which are related to freshwater habitat as well as vectors of diseases that affect domestic animals and humans in Africa are the snails (Rabone et al., 2019). However, the African

public health status of these snails seems uncertain despite the knowledge of how these freshwater faunas directly relate to different disease burdens (see; World Health Organization, 2020). For example, schistosomiasis caused by the *Schistosoma* parasite ranks as the second leading disease across Africa (Adekiya et al., 2020), and this might make the distribution of these snail species across Africa a public health concern. Since freshwater snails such as the *Bulinus* and *Biomphalaria* species are dominant snail species in the African freshwater environments (Rabone et al., 2019). Of course, these freshwater snail species are the major intermediate host of the trematode (*Schistosoma* species) that causes schistosomiasis. Across the African ecosystem, the *Bulinus* and *Biomphalaria* freshwater snails are composed of several species that host the trematode larval stage of the parasites (World Health Organization, 2020). Thus, the successful transmission of urogenital and intestinal schistosomiasis by these freshwater snail species across the African continent may be attributed to the expansion in the geographic distribution of these snails due to the significance of the suitability of the freshwater habitats to the in the African ecological region (Rabone et al., 2019; Adekiya et al., 2020). However, further studies comparing what environmental factors influence the abundance and concentration of the *Bulinus* species across the African ecological region to the other ecological regions will be interesting, perhaps to gain a comprehensive understanding of the simultaneous ecosystem and disease management in the context of the global rapidly changing climate.

More recently, human-induced environmental changes such as the creation of canals, hydroelectric dams, and irrigation scheme practices have been shown to reduce water quality and facilitate the geographical spread of some snail species across the freshwater ecosystems in Africa (World Health Organization, 2020). Presumably, climate variability in tropical areas such as Africa may be expected to influence the rise in the schistosomiasis burden in Africa (Abe et al., 2018). Because the *Bulinus* and *Biomphalaria* snail species as vectors of schistosomiasis mainly found across African freshwater have been suggested to be less vulnerable to human-induced environmental changes of the freshwater habitat they occupy

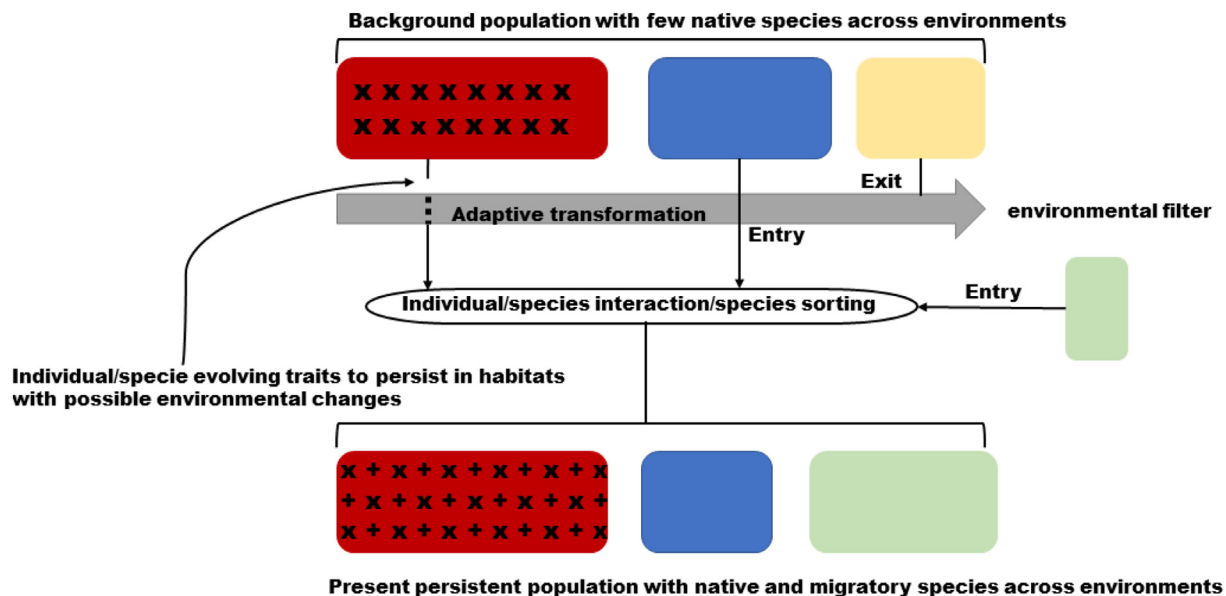


Fig. 1. Species sorting and environmental filters for determining mosquito population distribution and abundance in habitats across environments under the current rapid climate changes. The blue boxes represent how native mosquito species and/or individuals can persist during the transition periods across geographic gradients with different environmental conditions, while the green boxes depict non-native mosquito species and/or individuals from other regions entering and colonising the African ecosystems. Individuals or mosquito species achieve persistence in inhabited or recolonized African ecosystems by transformation (red and hatched boxes) through evolving persistence-plasticity that might lead to speciation. Additionally, interaction among individuals or species influenced by abiotic environmental conditions may shape individual and/or mosquito species persistence and persistence-plasticity in response to novel conditions posed by the changing climates Influencing environments occupied by mosquitoes across Africa. However, the yellow boxes represent individuals and/or species of African origin that are filtered out of environments because they can't withstand environmental changes. We proposed that species sorting and environmental filters for determining harmful insect populations, such as mosquitoes across environments in Africa, will follow a similar pattern earlier predicted for urban insect populations by (Chown and Duffy, 2015) because African territories do not live in isolation of the current rapid environmental changes.

(Adekiya et al., 2020). Although the freshwater habitats of the *Bulinus* and *Biomphalaria* snail species across Africa are constantly experiencing human-induced environmental changes that encourage climate change (McCreech et al., 2015). For instance, climate conditions have been shown to significantly influence schistosomes' longevity, fecundity, and transmission ability by snail species (McCreech et al., 2014). Thus, the rapidly changing climate across different ecological regions can alter the environmental suitability of freshwater habitats, that will directly or indirectly affect the abundance, concentration, and geographical re-distribution of snail species across freshwater ecosystems (Fig. 2).

4. Transmission patterns of freshwater vector-borne diseases

Major vector-borne diseases in Africa can be broadly categorized into snail-related (schistosomiasis) and mosquito-related diseases (malaria, Dengue fever and filariasis). These diseases are common in many developing countries due to factors such as lack of clean water, poor sanitation and inadequate healthcare facilities in African countries.

4.1. Mosquito-related vector-borne diseases

Malaria

Malaria is caused by protozoa belonging to the genus *Plasmodium*. It is an acute febrile illness caused by *Plasmodium* parasites, which are spread to people through the bites of infected female *Anopheles* mosquitoes. More than 400 different species of *Anopheles* mosquitoes exist, with about 70 species capable of transmitting malaria (Sinka et al., 2012). About five (5) *Plasmodium* species cause malaria in humans; 2 of these species – *P. falciparum* and *P. vivax* – pose the greatest threat. Particularly, *P. falciparum* is the deadliest malaria parasite and the most prevalent on the African continent (WHO, 2022a). According to World Health Organization, there are about 241 million cases of malaria worldwide, with Africa accounting for 95 %

of the cases (WHO, 2022a). And deaths as a result of malaria have been estimated to be about 627,000 globally, with Africa accounting for 96 % of the deaths. Nigeria (31.9 %), the Democratic Republic of the Congo (13.2 %), the United Republic of Tanzania (4.1 %) and Mozambique (3.8 %) are the most affected African countries (WHO, 2022a).

Based on previous studies, the longer life span and the human biting capacity of *Anopheles* mosquitoes that ultimately transmit the *Plasmodium* species (Fig. 3) in Africa have been reported to contribute to the high prevalence of malaria cases in this region (Mbacham et al., 2019). This is because malaria transmission depends on climatic conditions such as rainfall patterns, temperature, and humidity, which may affect the number and survival of *Anopheles* mosquitoes (Brady et al., 2013). And in many areas of Africa, transmission is seasonal, with the highest cases observed during the rainy season (Shililu et al., 2003). Although the initial symptoms of malaria (fever, headache and chills) are sometimes mild, it can cause severe illness and even death within 24 h if not well managed (Mbacham et al., 2019). Especially among people, such as infant children under five (5) years of age, pregnant women, patients with HIV/AIDS and people with compromised immunity moving to areas with concentrated malaria transmission, such as migrant workers, are particularly at risk of malaria (Mbacham et al., 2019).

Dengue fever

Dengue fever is a viral infection that is transmitted by the female *Aedes aegypti* mosquito (Fig. 4). Dengue virus (DENV) is transmitted to humans through the bites of infected female mosquitoes. So far, there are four (4) serotypes of DENV across the globe and all have been isolated in Africa, with DENV2 being responsible for most of the epidemics (Were, 2012). Infections of dengue result in flu-like illness and if not properly managed, can lead to a complicated type of dengue infection called severe dengue. Moreover, dengue is endemic to 34 countries in Africa, and *Aedes aegypti* mosquitoes are present in all African countries except Algeria, Morocco, Libya, Tunisia and Western Sahara (Were, 2012). In Africa, there have been some outbreaks in recent times, such as Cape Verde 2009 (16,744 cases,

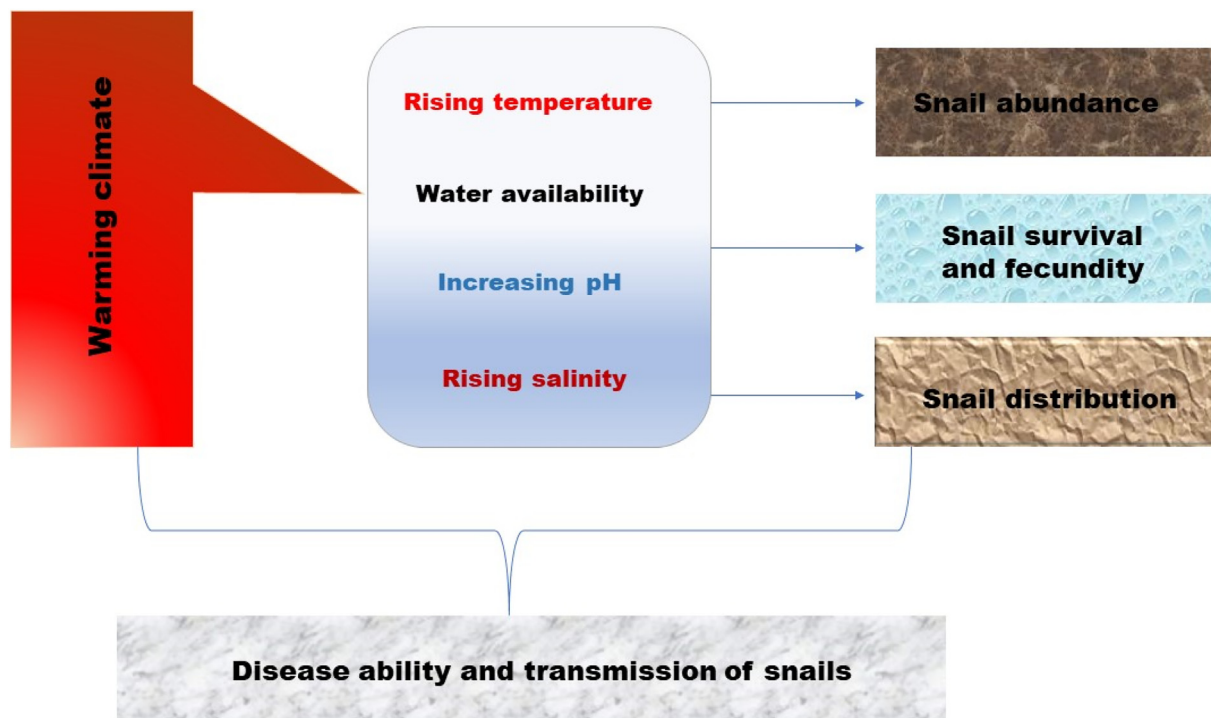


Fig. 2. Impact of the rapidly changing climate on freshwater snail fauna directly or indirectly affects Schistosomiasis transmission and burden. A warming climate scenario can lead to a rise in temperature, drought or flooding, rise in pH or salinity, and these are key environmental factors that directly impact snail species' reproduction, development, and survival. The reproduction success, development, and survival of the snails are important to the composition, geographical distribution, and abundance of these freshwater snails. Thus, a warming climate scenario can directly or indirectly affect the freshwater snail abundance and composition as the intermediate hosts of schistosomes, or the miracidia and cercariae of the schistosomes released into the freshwater environment.

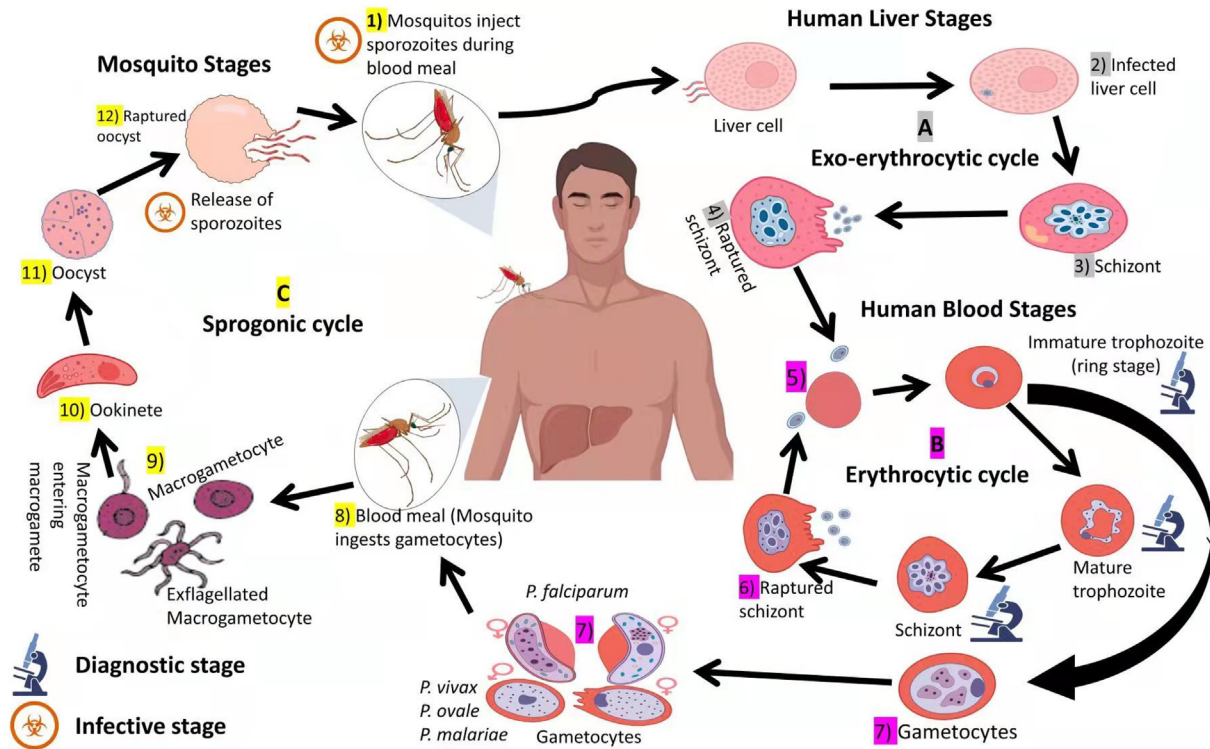


Fig. 3. Lifecycle of the malaria parasite adapted from (<https://www.cdc.gov/>) and modified for our study. This includes the exo-erythrocytic cycle (grey), erythrocytic cycle (purple) and the sporogonic cycle (yellow).

no deaths), Egypt 2015 (28 cases, no deaths), Burkina Faso 2016 (1266 cases, 15 deaths) and Côte d'Ivoire and Burkina Faso 2017 (9029 cases, 18 deaths) (Africa CDC, 2022).

Filariasis

Filariasis is notably one of the most commonly known mosquito-borne diseases globally. This infection arises as a result of exposure to mosquito

bites (Fig. 5). *Brugia malayi*, *Brugia timori*, and *Wuchereria bancrofti* are the three known causes of filarial infections in humans and are transmitted through *Culex*, *Anopheles*, and *Aedes* mosquitoes, respectively (Chakraborty et al., 2013). These parasites act by blocking the body's lymphatic vessels and nodes, resulting in the accumulation of fluids in tissues and subsequently leading to edema (lymphedema) (Liao and Padera, 2013). In Africa, filariasis is usually caused by *Wuchereria bancrofti*. According to World Health

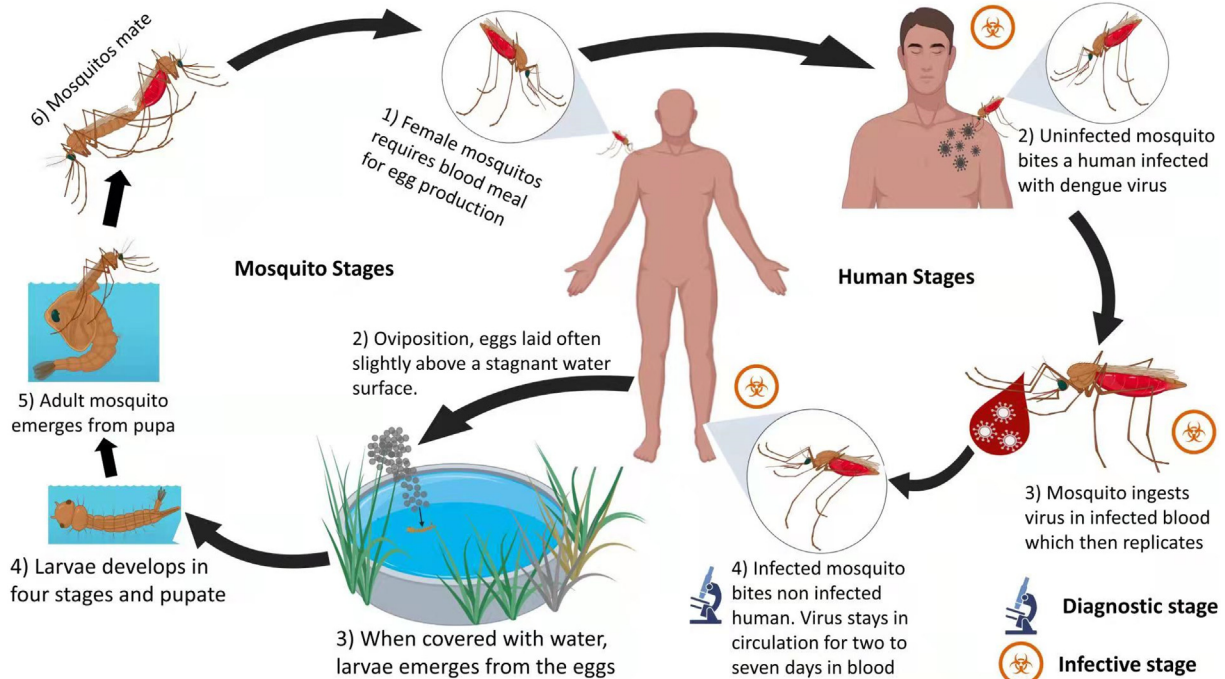


Fig. 4. Transmission of dengue fever virus and lifecycle of the mosquito vector adapted from (<https://www.cdc.gov/>) and modified for our study.

Organization, filariasis is a serious threat to about 406 million people in Africa (WHO, 2022b).

4.2. Snail-related vector-borne diseases

Schistosomiasis

Schistosomiasis, a snail-borne, fresh water-transmitted neglected tropical disease, is caused when an individual comes in contact with the blood flukes of *Schistosoma* (Fig. 6). It accounts for 250 million infections annually, with 779 million people potentially at risk (Chala and Torben, 2018). Ghana (15 million), the Democratic Republic of Congo (15 million), Mozambique (13 million), Nigeria (29 million) and Tanzania (19 million) have been reported to have the highest prevalence of Schistosomiasis (Adenowo et al., 2015; Aula et al., 2021; Onasanya et al., 2021). There are about five (5) known trematode species known to cause schistosomiasis in humans, namely: *Schistosoma mekongi*, *S. mansoni*, *S. haematobium*, *S. intercalatum*, and *S. japonicum* (Mohamed et al., 2018). The life-cycle of schistosome occurs in two known hosts: snails and mammals (humans, mice and dogs), via asexual or sexual reproduction, respectively. Asexual reproduction starts with miracidia developing into a sporocyst, which multiplies and develops into cercariae (Nelwan, 2019). During sexual reproduction, which occurs in mammalian hosts, parasites grow, mature, mate, and produce eggs. These mammalian hosts then release eggs of the worm into the environmental milieu either through faeces or urine. Following infiltration, the ciliated plates of the miracidium are removed, resulting in the development of the mother sporocyst and subsequent development into daughter sporocysts or cercaria (Mouahid et al., 2018).

In the mammalian hosts, the cercariae find their way into the human skin, where the forked tail is shed off to form a schistosomula. Upon entry into the body tissues via blood circulation, cercariae grow into schistosomes before becoming adult worms (Abe et al., 2018). The adult schistosomes contain the ZW and ZZ chromosome pairs for females and males, respectively. The adult worm can be found in several specific locations in humans which is specie-specific; for instance, *S. haematobium* in the bladder (Abe et al., 2018), ureters, or rectal venules, while *S. japonicum* is mostly found in the small intestine. Also, *S. mansoni* parasites are found in the large or small intestines (Abe et al., 2018). Cercariae-contaminated water can cause human schistosomiasis. Migration of infected persons from rural to

urban areas or vice versa can also lead to the spread of schistosomiasis and an outbreak of the disease. Awareness and orientation, as well as clean water supply, sanitation and vector control, can halt the spread of schistosomiasis.

5. Socio-economic and health impacts of water-related vector-borne diseases

Freshwater-related vector-borne diseases exert considerable debilitating impacts on people and areas affected. These impacts range from obvious health implications to equally pronounced social and economic consequences (Boutayeb, 2010). The burden of vector-borne diseases is mostly pronounced in the tropics, especially in Africa (Pant, 1987), where significant losses have been recorded in terms of monetary estimates and disability-adjusted life years (DALYs) – a metric for expressing the number of years lost due to illness, health impairment or untimely death.

The health effects of these vectors include illnesses such as malaria, lymphatic filariasis, schistosomiasis, onchocerciasis, Hemorrhagic dengue fever etc. These diseases have been reported to be responsible for complications, disabilities and, in severe cases, death. For example, malaria is a life-threatening disease transmitted by the female *Anopheles* mosquito was responsible for the death of over 600,000 people in 2020, with the African region bearing a disproportionately huge portion of 95 % of the global malaria burden. 80 % of the total malaria deaths in Africa occur among children under five (5) years, with the total disability-adjusted life years (DALYs) estimated to be 46,486,000 DALYs (WHO, 2021).

Several studies have reported differences in disease burdens across gender and ages. *Children* below five years are often the worst affected by these diseases, with significant morbidity and mortality, especially in less developed countries (Manetu and Karanja, 2021). It is further reported that incidence among children is higher in the “< 1-year-old” group, probably as a result of weaker immune systems (Bezerra et al., 2020). These are valid indicators of the need to develop age-specific and targeted disease control and prevention approaches. For instance, Bezerra et al. (2020) report slight differences in malaria incidence between the sexes. The study found that men in some geographical regions were reported to be at a higher risk of contracting malaria due to occupational peculiarities in the mining and forestry sectors. Conversely, a recent study found evidence for women

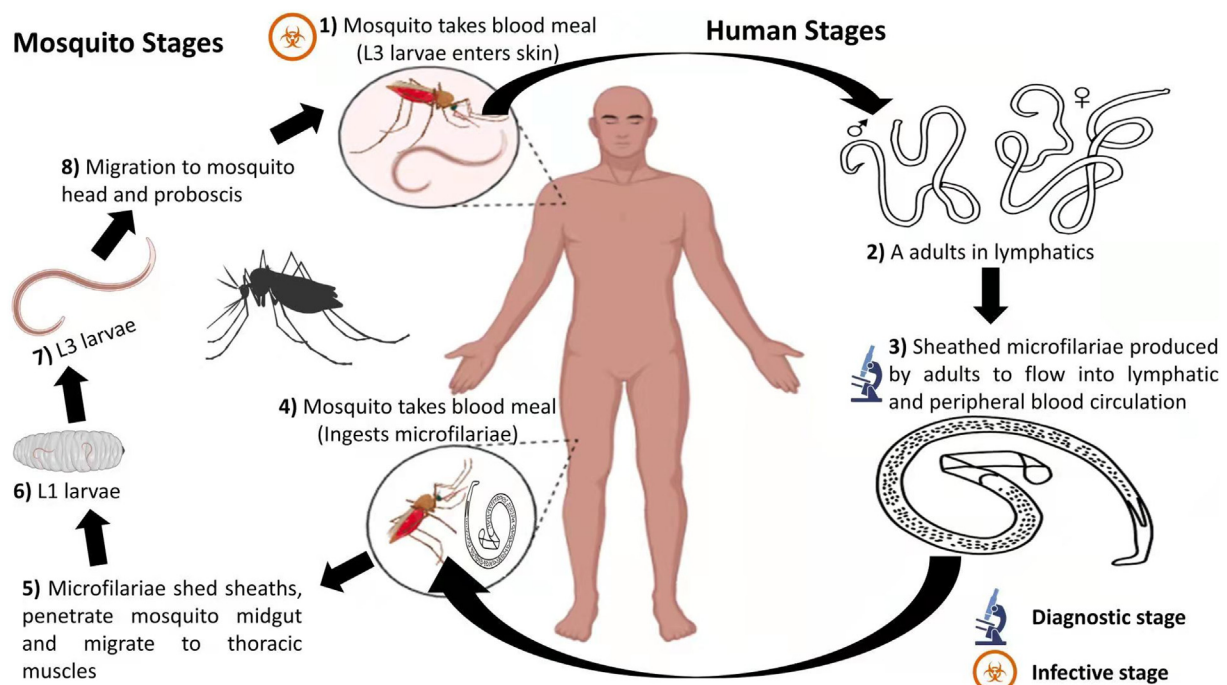


Fig. 5. Transmission of filariasis and lifecycle of the mosquito vectors adapted from (<https://www.cdc.gov/>) and modified for our study.

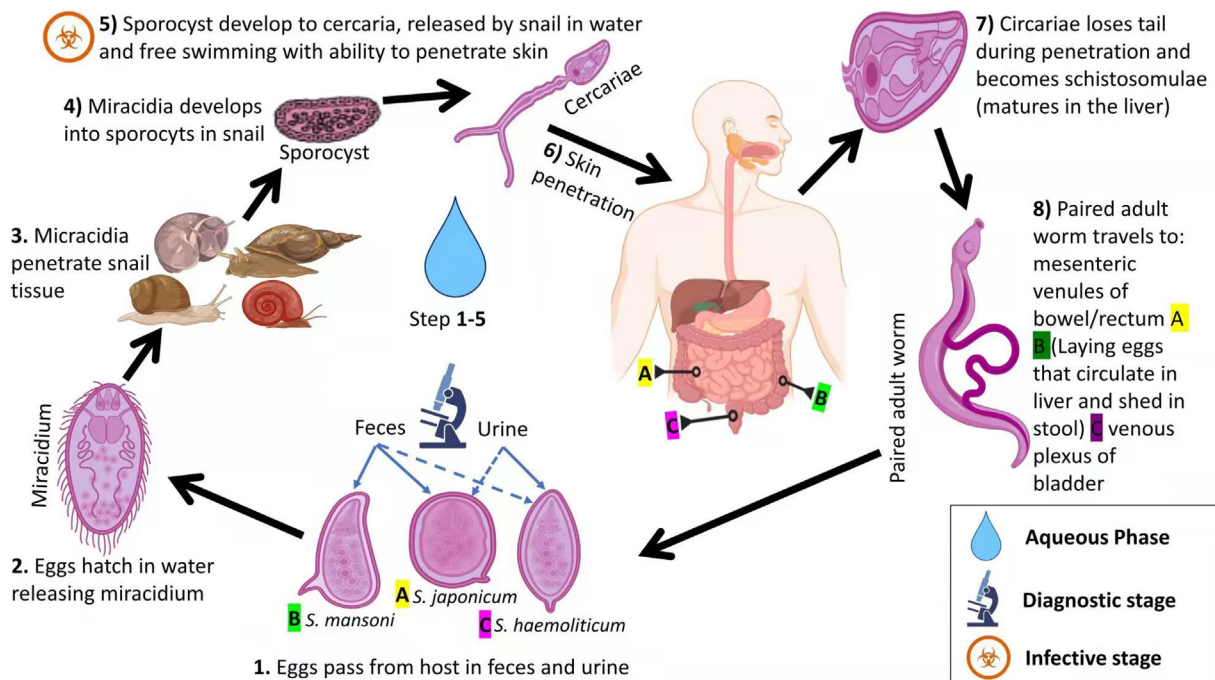


Fig. 6. Transmission of schistosomiasis adapted from (<https://www.cdc.gov/>) and modified for our study. The parasites infect the snail vectors and develop into cercaria during the aqueous stage. The cercaria penetrates the human skin and migrates to the liver, developing into the adult worm. Adult worms migrate to the bowel/rectum and lay eggs in the stool (yellow and green) or to the venous plexus of the bladder, where eggs are shed in urine (purple).

having a higher incidence, especially during pregnancy (Sanchez-Castro et al., 2022). Similarly, studies in Sudan (Abdalla et al., 2007) and South Africa (Mutegeki et al., 2018) corroborate that females had a higher DALY except in Ethiopia where males had higher DALYs as a result of public health interventions among pregnant women visiting antenatal clinics (Girum et al., 2019). Studies carried out in different regions of Africa also reveal interesting details about the seasonality of the health impacts of some vector-borne diseases such as malaria. For example, greater levels of malaria transmission occur in West Africa from September to November, which coincides with a little after the peak of the rainfall season (Diouf et al., 2020). However, studies have suggested that simulations of malaria incidence during drought predicted a decrease in vector abundance and malaria transmission, which might be due to the spatial and temporal variations in malaria transmission intensity (Shililu et al., 2003).

Another vector-borne disease of public health concern caused by mosquitoes is lymphatic filariasis. The WHO reports that 863 million people in 47 countries worldwide are endangered by lymphatic filariasis and need preventive chemotherapy to halt the escalation of this parasitic infection. Commonly known as elephantiasis, it causes fluid retention and tissue swelling in the limbs and genitals. In the later stages, it manifests as a painful enlargement and irreversible disfiguring of the legs and scrotum (hydrocele) (Ramaiah and Ottesen, 2014). Thus, lymphatic filariasis disease may have serious effects on self-esteem leading to shame and anxiety in leading individuals and may also render the sufferers incapable of money-generating activities (Ramaiah and Ottesen, 2014). Thus, the variations in the severity of DENV infections across different African regions have profound implications. However, this will require transboundary monitoring and surveillance of water-related vector-borne diseases in addition to integrated, multisectoral, collective action by countries and regions if studies apply the One Health Approach to reduce the burden of vector-borne diseases across Africa (Mackenzie and Jeggo, 2019).

Severe infections with DENV can sometimes prove lethal because there is currently no specific antiviral therapy except reliance on the host's immune response (Watts et al., 2020). These fatal manifestations include shock, fluid accumulation and severe bleeding. Encephalitis, myelitis and fulminant hepatitis have also been reported (Ling and Leo, 2007; Wasay et al., 2008). There are conflicting reports on the incidence and prevalence

of dengue virus disease. However, Eltom et al. (2021) report a high prevalence of Dengue virus infections across Africa. In addition, Simo et al. (2019) indicate a high variation in the distribution throughout several African regions. They describe disparities in DENV infection IgG seroprevalence between locations, ranging from 3.6 % in Eastern Africa to 52.6 % in Western Africa among participants with fever. In seemingly healthy subjects, IgG seroprevalence for DENV infection varied by area, ranging from 8.0 % in Southern Africa to 38.6 % in Central Africa. Similarly, the IgM seroprevalence ranged from 6.6 % in Western Africa to 35.2 % in Central Africa among febrile subjects. This frequency varied from 0.1 % in Central Africa to 5.0 % in Eastern Africa among asymptomatic subjects. The incidence of RNA in febrile individuals ranged from 5.3 % in Eastern Africa to 12.2 % in Central Africa.

Across the African continent, schistosomiasis has been found to be widely spread across the geographic boundaries of different countries (Adenowo et al., 2015). And school-aged children, women, and young adults have recorded significant morbidity. The disease is often associated with anaemia, growth retardation, fatigue, weakness, and memory impairment. This is in addition to nutritional disorders like nutrient malabsorption resulting from the worm invasion of the intestinal tracts. Urogenital schistosomiasis also increases HIV transmission from infected patients to their sexual partners (Mbabazi et al., 2011). Schistosomiasis is a disease of poverty as it affects people who wash, fish, and bathe in freshwater. We presume that there might be a vicious cycle between poverty and schistosomiasis. Because the continued use of contaminated water for domestic activities is due to poverty and lack of clean potable water (King, 2010). And the loss of livelihoods due to the effects of the disease ensures the continuance of poverty (King, 2010; Ugbomoiko et al., 2010). Perhaps, diseases like schistosomiasis might be endemic to low-income rural communities in Africa (Aula et al., 2021).

Nonetheless, some studies have shown high burdens of transmission reported in large, densely populated urban holoendemic settings, albeit among children (e.g., Brown et al., 2020). Thus, the transmission of these freshwater-related diseases has demonstrated clear patterns geographically and across different demographic groups. This calls for urgent action because diseases like schistosomiasis have serious economic significance (Whiteman et al., 2020). Aside from the disability-adjusted life years lost,

the financial resources required to control the spread of these diseases are enormous. Moreover, the deleterious effects of schistosomiasis on child development and even agricultural productivity in sub-Saharan Africa (Adenowo et al., 2015).

6. Impact of climate change on vector transmission and control

Climate change presents an enormous threat to the health and the general welfare of organisms (including humans) due to its ability to increase vector-borne disease transmission. Temperature-rise plus the continuous rise in rainfall and humidity generally affects vector population size, biting ability, survival, fecundity, rates of pathogen incubation, vectorial capacity, and geographical distribution (Mordecai et al., 2020; Peace, 2020). Other factors contributing to the spread of vector-borne diseases include human mobility (Malann et al., 2016; Deme et al., 2017a), urbanization, rainfall, and water storage practices (Deme et al., 2017b; Lehmann et al., 2021).

Africa is extremely vulnerable to vector-borne diseases due to rising temperatures, heavy precipitation, and inadequate vector management measures. *Anopheles* species are directly impacted by climate change; for instance, an increase in water temperature shortens the time of larval maturity and adult emergence, hence enhancing parasite fecundity and survival within the vector. In addition, it has been shown that African countries' optimal temperature and rainfall patterns influence the spread of mosquitoes. Flooding caused by persistent rainfall can increase the risk of malaria, dengue, yellow fever, etc. The rise in rainfall and maximum temperatures in Kenya's Baringo County has been linked to an increase in malaria cases with a 2-month lag. Similarly, during 2012 and 2016, Malawi saw a spike in malaria transmission at an ideal temperature of 24 °C. According to published research, the ideal temperature range for the spread of malaria is 16 to 27 °C, but a study conducted in Malawi showed that the risk of malaria increased at a maximum temperature of 30 °C. Heavy downpours and related events in South Africa resulted in a surge in malaria incidence from two to five months later. During the severe flooding, Uganda recorded a 30 % rise in malaria incidence. After a stretch of heavy downpours, similar cases of malaria incidence spikes were also confirmed in Zambia between 2008 and 2010. In Nigeria, Segun et al. (2020) discovered that rainfall considerably impacted malaria incidence at lag 1 month, but temperature and humidity also significantly impacted lag 4. The relationship between rainfall and the spread of malaria has direct and indirect trends in Papua New Guinea (Fouque and Reeder, 2019). Presently, there are cases of flooding in different parts of Africa, including Nigeria, which could lead to the outbreak of different infectious diseases.

The effects of temperature on disease transmission cannot be overemphasized; because high temperatures can lead to the migration of vector species to a novel area, thus resulting in the incident of vector-borne disease in that area. For example, empirical studies have found that *Anopheles* species have their peaks of activities at a temperature of 25 °C, while *Aedes* species have their activity peaks at a temperature of 29 °C (e.g., Mordecai et al., 2020). However, extreme temperatures affect their development and survival (McCreesh et al., 2015; Mordecai et al., 2020). Thus, extreme temperatures can lead to either adaptation, migration from their original habitats to a novel environment, or extinction of species (Fig. 1). This can result from shifting the disease pattern and outbreak of arthropod-borne diseases in a new area where such diseases have not been recorded for the first time.

Tropical regions with an average temperature above 25 °C may support vector-borne diseases such as dengue, chikungunya and other arboviruses since *Aedes aegypti* thrives more at the temperature of 29 °C and *Anopheles* species decreases its general activities at 25 °C (Mordecai et al., 2020). Perhaps, this may explain the recent outbreaks of several arbovirus-related diseases across tropical regions like Africa. Unsurprisingly, recent studies are projecting that malaria burden is expected to shift toward higher elevations, such as the Albertine Rift region and higher latitudes in Southern Africa, while diseases transmitted by *Aedes aegypti* are predicted to expand from West Africa throughout sub-Saharan Africa (e.g., Lehmann et al., 2021). For example, an increase in *Anopheles gambiae* has been observed in Madagascar, with an increase in malaria incidence in Colombia, Ethiopia, Papua New Guinea, and

Baringo County in Kenya (Fouque and Reeder, 2019). This is because the higher temperature has been associated with the distribution of *Anopheles arabiensis* on the slope of Mount Kilimanjaro, thus leading to a subsequent change in malaria distribution (Fouque and Reeder, 2019).

Furthermore, the high rate of deforestation due to Agricultural practices in rural areas across Africa brings more humans to the forest area, thus leading to the close interaction between humans and these wild species of mosquitoes (Eastwood et al., 2020). Recent studies have shown that the unlogged forest area across Africa had the highest number of Mosquito species in richness and abundance when compared to the undisturbed forest area in Cameroon (Paul et al., 2019). This suggests that deforestation or changes in land use (from tropical forest to agricultural lands) creates new habitat features for mosquitoes, which can lead to the breeding of sylvatic species (for instance, the discovery of *Anopheles arabiensis*). Furthermore, exploitation of land due to agricultural expansion leads to an increase in Malaria cases among children of 5 years and below across sub-Saharan Africa (Zahouli et al., 2017; Shah et al., 2022). Thus, the resultant associations of wild mosquitoes to humans might be influencing the increasing expansions and outbreaks of mosquito-borne diseases, which could be frustrating the possible achievement of the African Union Millennium goal of Zero mosquito-borne diseases by 2030.

Perhaps, we may speculate that the increasing expansions and outbreaks of mosquito-borne diseases remain a great burden to public health due to the lack of enough preparedness in place for tackling these diseases and vector control schemes in Africa. Although the obvious of climate change on mosquito-borne diseases in Africa are enormous (McCreesh et al., 2014). But we still have paucity of epidemiological data due to poor surveillance, inadequate health information systems, and insufficient research funding. Thus, critical surveillance and an effective integrated vector management system (IVM) are seriously needed to tackle the emergence and resurgence and the geographic expansion of vector-borne diseases, drug and insecticide resistance, and the impact of climate change on vector-borne diseases (Lehmann et al., 2021).

7. Mosquito and snail vector control

In the past, different control measures on vectors such as mosquitoes and snails have been implemented across Africa (Table 1). Most prominent was the use of DDT to control adult female mosquitoes across Africa was introduced (Sougoufara et al., 2017). Despite the success of controlling the *Anopheles* mosquito population across Africa, it was not sustainable because of its impact on the environmental and associated resistance. For instance, DDT mostly persists in the environment for a long time, thus affecting the food chain (Sougoufara et al., 2017). However, most recently, the use of insecticide-treated bed nets (ITNs), indoor residual spraying (IRS), and larvae control approaches against mosquito vectors have been observed across some African countries (Tonglet et al., 2004; Oyinloye et al., 2014; Tesfazghi et al., 2016). For example, Tanzania, in the quest to eradicate vector-borne diseases, has adopted the following control methods: indoor residual spray, long-lasting insecticide nets (LLINs), larval source management (LSM), use of repellents, use of coils, fumigation and house modification (Kweka et al., 2017; Makungu et al., 2017).

The chemical method used in the control of molluscs includes the use of Molluscicides like metaldehyde, methiocarb, and iron Phosphate. The molluscicides are somewhat not completely effective across species and are not environmentally friendly. For instance, metaldehyde, a molluscicide that did not completely eradicate the snail population, was found to be toxic to non-target fish populations when it is swept into the water by a flood (Robert et al., 2007). Despite this knowledge, some African countries still use this approach to control their snail population (de Carvalho Augusto and Mello Silva, 2018). Thus, effective vector control might be threatened by the increasing use of chemicals across African countries. Consequently, the need to introduce and use advanced techniques for better controlling mosquito and snail vectors.

Recently, biological control such as the use of poison baits, trapping, habitat manipulation, and *Bacillus thuringiensis* (Bti) that inhibit the

Table 1
Summary of vector management approaches currently or previously used across Africa.

Vector control	Vector	Positives	Environmental effects	Challenges
Aerial spraying of insecticides	Mosquitoes	Reduction in the population of <i>Aedes</i> and <i>Culex</i> mosquitoes	Non-biodegradable due to accumulation of toxic chemicals like DDT	Insecticide resistance. Change in behaviour of vectors.
Insecticide-treated bed nets (ITNs)	Mosquito species	Reduction in indoor biting of mosquito	Biodegradable	Unable to totally control mosquito populations
Toxic sugar baits	Mosquitoes	Reduction in adult mosquitoes	Biodegradable	Target a small population of mosquito vectors
Use of coils	Mosquitoes	Reduction of adult mosquitoes indoors	Biodegradable	Target a small population of mosquito vectors
Mosquito-proofed housing	Mosquitoes	Reduction of human exposure to mosquitoes' bite	Biodegradable	Not affordable to low-income earners
Larval source management (LSM)	Mosquitoes	Reduction of adult mosquitoes' emergence	Environmentally safe	Change in vector ecology affects habitats and the season of larval emergence
Adult sterilization by contamination	Mosquitoes and snails	Decrease in fecundity and low population of vectors	Environmentally safe	Costly and difficult to maintain female <i>Anopheles</i>

Some of the methods reported were adapted from Williams et al. (2018) and modified for our study.

development of *Anopheles* mosquito larvae in breeding grounds have been in used across some African countries (Robert et al., 2007). For example, a large-scale application of bioinsecticide *Bacillus thuringiensis* and *israelensis* (Bti) in Burkina Faso dramatically decreased the number of mosquitoes across the country (see; Sougoufara et al., 2020). Additionally, *Bacillus sphaericus* (Bs) and (Bti) combined with ITN resulted in significantly lower *Anopheles* species vector densities across some countries in the Sub-Saharan African ecosystem, resulting in reduced malaria transmission in some regions (Sougoufara et al., 2020). However, the challenge and limitations of this larval control method are that it might not be effective across all mosquito species, especially for mosquito species with numerous and inaccessible breeding colonies or when it is used on a large scale (Sougoufara et al., 2020). This is because diverse mosquito species are known to differ in their behaviours breeding behaviours and sites (Olayinka, 2019). Except if this larva control method will be applied on small scales across all breeding sites, which might be capital intensive. Thus, the integrated vector management (IVM) approach might be necessary to reduce the rising populations of vectors of diseases like mosquitoes and snails. This is because applying one approach to vector population control may not yield the required results needed amidst continuous growth in vector populations. We suggest that future studies might need to consider adopting advance genetics methods of vector control such as Sterile Insect Technique (SIT), Incompatible Insect Technique (IIT), Ionizing Radiation, and Gene Drive/Gene Editing.

8. Conclusion and directions for future studies

Our study highlights the need to consider the ecology of vectors in the environment and control freshwater disease risk factors across diverse sectors, locations, and scales in Africa. Because the population, distribution and/or abundance of these freshwater organisms are increasing, which is directly associated with the emerging and re-emerging vector-borne diseases across Africa. Furthermore, the current changing environmental conditions in Africa, which affect the habitats of these freshwater organisms, are not affecting the population distributions or abundance of these freshwater organisms. Instead, freshwater organisms in Africa may be extending their geographic ranges across Africa due to their ability to evolve traits that will help them to adapt to the changing environmental conditions. And this may have significant public health implications in Africa.

The frequent contamination and degradation of Africa's freshwater environments have probably greatly altered the freshwater habitats, which may be aiding the spread of disease-causing organisms and increased disease vector breeding sites. However, despite the dangers of freshwater vectors, Africa as a continent might not be properly managing the increasing expansions and outbreaks of vector-borne diseases that remain a major public health issue. This is worrying because of the increasing regional abundance and distribution of freshwater vectors and their ecological roles in transmitting diseases. Studies have suggested a public health

resolution approach to use the One Health approach for Africa's emerging and re-emerging threat of infectious diseases. Thus, to understand factors leading to the increasing expansions and outbreaks of vector-borne diseases, we propose that it is critical to incorporate the framework of vector-related environmental conditions into public health education and future management studies. This is because only a few studies have attempted this approach, which is a significant shortfall in the knowledge of freshwater vectors in developing a clear understanding of their transmission and development in the context of vector-related environmental conditions (Smit et al., 2020).

Additionally, biotechnological techniques like next-generation sequencing, including genetic and molecular characterization, could reveal the genetic epidemiology required for effective vector and parasite population surveillance and cryptic diversification of vectors such as mosquitoes in Africa. Furthermore, studies have advocated addressing the shortcomings in Africa's vector ecology by strengthening the capacity of laboratories to detect vector-borne diseases and consolidating efficient and integrated vector surveillance, such as field surveys, ecological niche modelling and biotechnology and vector control programs for the effective maintenance of overall public health (Buchwald et al., 2020). The development of reliable point-of-care diagnostics, improved diagnostic tools as well as surveillance kits for water-related vector-borne diseases in Africa, for malaria, dengue, and chikungunya vectors, as well as community-based vector control initiatives, will be critical for targeted therapy and disease prevention (Mordecai et al., 2020) since Africa urgently needs to strengthen water-vector surveillance and control through capacity building and research.

CRedit authorship contribution statement

All authors contributed equally to the conceptualization, data curation, writing and editing of all manuscript drafts.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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