Urban malaria in sub-Saharan Africa: dynamic of the vectorial system and the entomological inoculation rate

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Abstract
Sub-Saharan Africa is registering one of the highest urban population growth across the world. It is estimated that over 75% of the population in this region will be living in urban settings by 2050. However, it is not known how this rapid urbanization will affect vector populations and disease transmission. The present study summarizes findings from studies conducted in urban settings between the 1970s and 2020 to assess the effects of urbanization on the entomological inoculation rate pattern and anopheline species distribution. Different online databases such as PubMed, ResearchGate, Google Scholar, Google were screened. A total of 90 publications were selected out of 1527. Besides, over 200 additional publications were consulted to collate information on anopheline breeding habitats and species distribution in urban settings. The study confirms high malaria transmission in rural compared to urban settings. The study also suggests that there had been an increase in malaria transmission in most cities after 2003, which could also be associated with an increase in sampling, resources and reporting. Species of the Anopheles gambiae complex were the predominant vectors in most urban settings. Anopheline larvae were reported to have adapted to different aquatic habitats. The study provides updated information on the distribution of the vector population and the dynamic of malaria transmission in urban settings. The study also highlights the need for implementing integrated control strategies in urban settings.

Keywords: Malaria, Urbanization, Sub-Saharan Africa, Anopheles, Entomological inoculation rate, Bionomic

Background
Sub-Saharan Africa still bears the highest burden of malaria morbidity and mortality worldwide despite improvements in the diagnostic of the pathogens and large-scale deployment of vector control measures, such as Long-Lasting Insecticidal Nets (LLINs) and Indoor Residual Spraying (IRS) [1]. In 2019 over 229 million cases and 409,000 deaths were recorded across the world [1]. Although the whole sub-Saharan Africa region is exposed to malaria transmission risk, high heterogeneity in malaria transmission patterns exists on the continent, particularly between urban and rural settings [2–4]. It is considered that people living in rural settings are more exposed to malaria transmission risk compared to those living in urban settings [3, 5]. Studies conducted so far suggested higher densities and a greater diversity of malaria vector population sizes in rural compared to urban settings [6]. Many factors have been reported to affect malaria transmission intensity in urban settings including pollution, which can affect anopheline larval habitats and reduce their population size as well as impact mosquito life cycles and consequently their vectorial capacity. Urban dwellers may also have greater

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mosquito avoidance behaviour, including the use of repel-
ents, screens on windows, insecticides spray and coils [2,
7–9]. During the last decade, sub-Saharan Africa regis-
tered an unprecedented growth of it urban population.

The urban population which was estimated at 491 mil-
lion in 2015 is projected to grow to nearly 1.5 billion by
2050 [10]. However the rapid unplanned urbanization
observed in many sub-Saharan Africa cities character-
ized by the colonization of lowland areas for house con-
struction, the absence of drainage system for water, the
presence of standing water collection everywhere due
to the bad state of roads and poor housing are all con-
sidered to affect the distribution of vector population
and malaria transmission pattern [11]. Now, many cit-
ies are reporting increase practice of urban agriculture
in both the city centre and periphery; all these activi-
ties create favourable breeding habitats for mosquitoes
[12–14]. The rapid unplanned urbanization appears as
a potential risk factor promoting malaria and arboviral
diseases transmission in urban settings [15, 16]. Studies
conducted so far suggested higher densities and a greater
diversity of malaria vectors in rural compared to urban
settings [2, 6, 17]. Besides, it has been reported that the
most efficient malaria vectors Anopheles gambiae sensu
lato (s.l) namely Anopheles gambiae, Anopheles coluzzii,
Anopheles arabiensis, which had a strong preference for
unpolluted water [13] now displays a great adaptation
pattern to polluted waters in urban cities [18, 19] and
breed in different human-made habitats including con-
tainers filled with water, swimming pools, tyre tracks,
water tanks [20]. Housing construction sites or construc-
tion materials were also found to be productive habitats
for malaria vectors [21, 22]. The situation of malaria in
sub-Saharan African cities is further becoming complex
with the recent invasion of the Asian malaria vectors
Anopheles stephensi [23, 24]. Although the epidemiologi-
ical consequences of such invasion is still not well under-
stood, it is likely that the addition of new competent
vectors in the urban environment may further negatively
affect malaria control strategies in urban areas. Conside-
ring the potential public health impact that urban malaria
could have and potential effects on the economic devel-
opment of countries, there have been during the last
decade a renewed interest with several studies assess-
ing malaria transmission pattern and vector bionomic
in urban settings across sub-Saharan Africa [11, 18, 21,
25–29]. However there have been so far not enough stud-
ies summarising findings from previous works in order to
capture the general trend of malaria transmission, vec-
tor distribution and larvae preferred breeding habitats in
urban settings. For instance, there have been fewer stud-
ies providing an overview of the general distribution pat-
tern of main species in urban settings across Africa. The

present study's objective is to carry out a review of the
existing literature on malaria transmission across sub-
Saharan Africa in order to provide a better understand-
ing of the evolution of vector populations and malaria
transmission pattern.

Methods

Literature search

A search for studies on urban malaria in Africa was con-
ducted to capture the general trend of malaria trans-
mission using the following online databases PubMed,
Research Gate, Google scholar and Google. Search
terms included a combination of key words such as “EIR
Anopheles”, “Urban malaria”, “malaria urban SSA”, “Africa
mosquitoes”, “malaria transmission”, “Urbanization”, “cit-
ties”, “malaria Pl. falciparum”, “malaria epidemiology”,
“urban population”, “malaria prevalence”.

Literature selection process

The selection included papers published between the
1970s to 2020. Initial selection using the above combina-
tion of keywords yielded a total of 1527 scientific publica-
tions. All studies not conducted in Africa were discarded
(n = 381). The remaining papers were then selected using
the following criteria (i) description of malaria transmis-
sion or prevalence in urban and/or rural and/or periur-
ban settings; (ii) studies conducted in sub-Saharan
Africa. Papers which did not estimate the EIR or malaria
prevalence or appearing several times in the selection
were also excluded from the review. After applying this
selection criteria, 1047 studies were discarded. Further
reading of the abstract and the whole paper permitted
to exclude an additional 9 papers living 90 for the study
(Fig. 1).

Besides, an additional selection was performed to col-
late information on breeding habitats and anopheline
species distribution in urban cities. Over 200 scientific
publications were consulted for this purpose. Terms used
to guide this search included the name of main cities in
West, East and Central Africa followed by a combina-
tion of key words such as “malaria Anopheles”; “malaria
Anopheles larvae”; “Anopheles urban breeding sites”,
“Anopheles aquatic habitats”.

Data analysis

Available information retrieved from each selected
publication were registered in a Microsoft Excel
spreadsheet for data analysis. This included authors
names, the year of publication, country, study site,
types of settings, sampling method, study type, malaria
transmission indices (entomological inoculation rate
(EIR), human biting rate (HBR)), vectors involved in
the transmission, abundance of vectors, study period, malaria prevalence, and parasites (Additional file 1).

EIRs estimates were not always available in selected papers in an adequate format for analysis. The following steps were taken in order to adjust data presentation. (i) When many EIRs were estimated for the same site (EIRs for districts within a city), the average EIR from the area was estimated and used for analysis; (ii) when the EIR value was presented for two different periods in the same site, the highest value was considered; (iii) when indoor and outdoor EIRs were reported, the EIRs were summed to have the total EIR from the area; (iv) when EIRs were presented as daily or monthly or seasonal EIRs, the annual EIR was estimated.

The Spearman correlation coefficient was used to assess the correlation between EIRs and biting rates. The Kruskal–Wallis and Mann–Whitney tests were used to compare EIRs averages between urban, periurban and rural settings. The EIR was also compared between periods before 2003 and after 2003 because after 2003 studies conducted were using more molecular tools for mosquito processing (PCR, ELISA) than before. Analyses were performed using R software version 3.4.0 and GraphPad Prism 7.

Study design
A flowchart representing the study design show data collected in selected papers, indicators assessed and comparisons performed in the review (Fig. 2).

Results
Literature review of EIR estimates in rural, periurban and urban settings
A total of 90 studies conducted in 136 sites in 23 countries were consulted for the present review (Table 1). Data presented derive from studies in 88 rural sites, 18 periurban sites and 31 urban sites.

Dynamic of the EIR between rural, periurban and urban settings
A high heterogeneity in EIR estimates was recorded between urban, periurban and rural settings. The average EIR was 144.05 infective bites per person per year (ib/p/yr) 95% CI [141.9–146.22] in rural area, 45.70 ib/p/yr 95% CI [42.86–48.7] in periurban area and 32.73 ib/p/yr 95% CI [31.13–34.38] in urban sites. A significant difference was recorded when comparing the EIR between rural, periurban and urban areas (P < 0.05). When comparing EIR estimates of the urban
centre between the period before 2003 (1977–2003) and the period after 2003 (2004–2020) it appears a significant increase in malaria transmission estimates in urban centres since 2003 (P = 0.0001), no such increase was recorded for periurban and rural settings (Fig. 3).

Evolution of EIR in main sub-Saharan Africa cities
When comparing the EIR estimates in urban centres between 1977 and 2020, it appears that before 2003 there were many cities reporting very low or no transmission of malaria from mosquitoes to man whereas between 2004 and 2020 almost all studies indicated evidence of malaria transmission (Fig. 4). Average EIR values varying annually from 30 to 100 ib/p/yr were recorded in most urban settings (Fig. 4). Extreme values of EIR above 500 ib/p/yr have also been reported in Yaoundé [30] and Bioko [31], but these values were not included in the present analysis. *Plasmodium falciparum* was the main parasite detected in most cases.

Larval sites distribution in urban area
*Anopheles* larvae were frequently found in man-made water habitats, such as drains, puddles, market gardens, urban agricultural sites, pools drains and tyre tracks. *Anopheles* larvae were also reported in natural breeding sites such as swamps, streams or rivers bed although they are less common and scattered in urban areas. The number of studies highlighting the specific breeding sites of anopheline in urban areas both natural and artificial is presented in Table 2.

Diversity of the Anopheline fauna in urban cities
A total of 12 anopheline species were reported in studies conducted in urban cities. Species of *An. gambiae* complex, including *Anopheles gambiae* sensu stricto (s.s.), *Anopheles coluzzii* and *Anopheles arabiensis* were the most common. Additional species present in urban settings included *Anopheles melas*, *Anopheles funestus* s.s. and *Anopheles stephensi*. Other anopheLINE species such as *Anopheles coustani*, *Anopheles*
| Authors                      | Year | Country   | Locality          | EIR   |
|------------------------------|------|-----------|-------------------|-------|
| Abraham et al. [78]          | 2017 | Ethiopia  | Sille             | 63.6  |
| Akogbeto et al. [79]         | 2000 | Benin     | Cotonou           | 12    | 47   | 29   |
| Adja et al. [80]             | 2011 | Côte d’ivoire | Gbatta, Kpehiri | 298.8 | 478.8 |
| Akono et al. [30]            | 2015 | Cameroon  | Akonolinga, Yaoundé | 813.95 | 552.61 |
| Akono et al. [81]            | 2015 | Cameroon  | Logbessou         | 47.28 |
| Antonio-Nkondjio et al. [82] | 2002 | Cameroon  | Simbock           | 368   |
| Antonio-Nkondjio et al. [14] | 2012 | Cameroon  | Douala            | 31    |
| Amawulu et al. [83]          | 2016 | Nigeria   | Bayelsa           | 80.5  |
| Amek et al. [84]             | 2012 | Kenya     | Nyanza            | 26.6  |
| Amvongo-Adjia et al. [85]    | 2018 | Cameroon  | Tiko, Manfe, Santchou | 8.4;16.8;26.88 |
| Appawu et al. [86]           | 2004 | Ghana     | Kassera Nankana   | 1218  |
| Beier et al. [45]            | 1993 | Cameroon  | Kisian, Saracidi  | 299;237 |
| Bockarie et al. [87]         | 1994 | Sierra Leone | Bo              | 21–36 |
| Cano et al. [31]             | 2004 | Equatorial Guinea | Bioko     | 814.27 |
| Cano et al. [88]             | 2006 | Equatorial Guinea | Yengue    | 298.8 |
| Carnevale et al. [89]        | 1985 | Congo     | Brazzaville      | 80–850 |
| Carnevale et al. [90]        | 1992 | Cameroon  | Mbebe            | 182   |
| Coene [91]                   | 1993 | RD Congo  | Kinshasa          | 455   |
| Degefa et al. [92]           | 2015 | Ethiopia  | Jimma            | 0–4781.5 |
| Diallo et al. [93]           | 1998 | Senegal   | Dakar            | 0     |
| Diallo et al. [94]           | 2000 | Senegal   | Dakar            | 0     |
| Daygena et al. [95]          | 2017 | Ethiopia  | Gato             | 103.2 |
| Elissa et al. [96]           | 1999 | Gabon     | Franceville      | 365   | 81   |
| Epopa et al. [97]            | 2019 | Burkina Faso | Bana, Pala, Souroukoudingan | 393.47;199.65;151.84 |
| Getachew et al. [98]         | 2019 | Ethiopia  | Ghibe            | 13.8  |
| Lwetoijera et al. [99]       | 2014 | Tanzania  | Kilombero        | 392.31 |
| Djamouko-Djonkam et al. [37] | 2020 | Cameroon  | Yaoundé          | 106.83 | 9.78 |
| Dossou-yovo et al. [100]     | 1995 | Ivory Coast | Bouake          | 230   |
| Dossou-yovo et al. [101]     | 1994 | Ivory Coast | Bouake        | 126.88 |
| Doumbe-Belisse et al. [11]   | 2018 | Cameroon  | Yaoundé          | 0–92  |
| Drakeley et al. [102]        | 2003 | Tanzania  | Ifakara          | 30.7  |
| Fontenille et al. [103]      | 1992 | Madagascar | St Marie Island | 100   |
| Fontenille et al. [104]      | 1997 | Senegal   | Dieimbo          | 159   |
| Fontenille et al. [105]      | 1997 | Senegal   | Ndiop            | 31    |
| Fouque et al. [106]          | 2010 | French Guinea | Loca, Twenke    | 10;5  |
| Govoetchan et al. [107]      | 2014 | Benin     | Sonsoro, Ganssosso | 130.75 | 6.45 |
| Hakizimana et al. [108]      | 2018 | Rwanda    | Karambi, Mashesha, Kicukiro | 1–329.8 | 107.5 |
| Himeidan et al. [109]        | 2011 | Sudan     | Koka, Um Salala  | 109.5;3.65 |
| Karch et al. [110]           | 1992 | Congo     | Kinshasa         | 620   | 66   | 3    |
| Kasasa et al. [111]          | 2013 | Ghana     | Navrongo         | 1.132–157 |
| Kerah-Hinzoumbé [112]        | 2009 | Chad      | Goulmoun         | 311   |
| Kibret et al. [113]          | 2014 | Ethiopia  | Ziway            | 0.25–27.3 |
| Klinkenberg et al. [13]      | 2008 | Ghana     | Accra            | 6.6–19.2 |
| Krafsur et al. [114]         | 1977 | Western Ethiopia | Gambela    | 97    |
| Lemasson et al. [115]        | 1997 | Senegal   | Barkedji         | 114   |
| Lindsay et al. [116]         | 1990 | Gambia    | Banjul           | 1.3   |
| Lochouarn et al. [117]       | 1993 | Burkina Faso | Bobo-Dioulasso  | 2     |
| Gadiaga et al. [118]         | 2011 | Senegal   | Dakar            | 17.6  |
Table 1 (continued)

| Authors          | Year  | Country     | Locality          | EIR       | Rural | Periurban | Urban |
|------------------|-------|-------------|-------------------|-----------|-------|-----------|-------|
| Githeko et al. [119] | 1993  | Kenya       | Ahero             | 91–416    |       |           |       |
| Machault et al. [28] | 2009  | Senegal     | Dakar             |           |       | 0–168     |       |
| Mala et al. [120] | 2011  | Kenya       | Kamarimir, Tirion | 1.44; 1.61|       |           |       |
| Manga et al. [121] | 1992  | Cameroon    | Yaoundé           | 3, 13     |       |           |       |
| Massebo et al. [122] | 2013  | Ethiopia    | Chano             | 0–73.2    |       |           |       |
| Mbogo et al. [123] | 2003  | Kenya       | Malindi           | 0–120     |       |           |       |
| Mbogo et al. [124] | 1993  | Kenya       | Kilifi            | 8         |       | 1.5       |       |
| Mbogo et al. [125] | 1995  | Kenya       | Kilifi            | 0–59.6    |       |           |       |
| Mourou et al. [39] | 2012  | Gabon       | Libreville        | 33.9      |       |           |       |
| Mourou et al. [41] | 2010  | Gabon       | Libreville, Port-Gentil | 3.45;66.45|       |           |       |
| Mutuku et al. [126] | 2011  | Kenya       | Kidomaya, Jego    | 5.16      |       |           |       |
| Muturi et al. [127] | 2008  | Kenya       | Kiamachiri, Mbujieru, Murinduko | 4.06; 2.55; 2.50|       |           |       |
| Mwangangi et al. [128] | 2013  | Kenya       | Kimudia, Kiwalwa, Mwarusa, Njoro | 31.95; 123.92; 59.78; 45.06|       |           |       |
| Mwanziza et al. [129] | 2011  | Tanzania    | Gichamera         | 0.51      |       |           |       |
| Ndenga et al. [130] | 2006  | Kenya       | Iguhu, Kombewa, Marani, Mbale | 16.6;31.1;0.4;1.1|       |           |       |
| Njan Nloga et al. [131] | 1993  | Cameroon   | Ebogo             | 355       |       |           |       |
| Okello et al. [132] | 2006  | Uganda      | Jinja, Arua, Apac, Tororo, Mubende, Kyenjojo, Kanungu | 397; 1586; 562; 4; 7; 6|       |           |       |
| Okwa et al. [133] | 2009  | Nigeria     | Bungudu-Gusau, Badagry, Onitsha, Bonny | 23.31    |       | 74.1;32.1; | 34.5 |
| Olayemi et al. [134] | 2011  | Nigeria     | Ilorin and Minna | 0.83      |       |           |       |
| Overgaard et al. [135] | 2012  | Equatorial Guinea | Bioko              | 163–840   |       |           |       |
| Owusu-Agyei et al. [136] | 2009  | Ghana       | Kintampo          | 269       |       |           |       |
| Richard et al. [137] | 1988  | Congo       | Mayombe           | 80; 397   |       |           |       |
| Robert et al. [89] | 1985  | Burkina Faso | Bobo-Dioulasso    | 50; 60; 55; 133|       |           |       |
| Robert et al. [138] | 1986  | Burkina Faso | Bobo-Dioulasso    | 5         | 0.105 |           |       |
| Robert et al. [139] | 1993  | Cameroon    | Edea              | 4; 30     |       |           |       |
| Robert et al. [140] | 1998  | Senegal     | Niakhar           | 9; 12.26  |       |           |       |
| Rossi et al. [141] | 1986  | Burkina Faso | Ouagadougou       | 92.82; 430| 10; 23 | 7.00      |       |
| Salako et al. [50] | 2018  | Benin       | Alibon, Donga     | 285.48    |       | 49.8      |       |
| Shiff et al. [142] | 1995  | Tanzania    | Coastal Tanzania  | 94–703    |       |           |       |
| Shililu et al. [143] | 2003  | Eritrea     | Anseb, Debub, Gash-Barka, Northern Red Sea | 3.45; 15.95; 66.45; 0 |       |           |       |
| Smith et al. [144] | 1993  | Tanzania    | Kilombero         | 329       |       |           |       |
| Tabue et al. [145] | 2017  | Cameroon    | Garoua, mayo Oulo, Pitoa | 71.54 |       | 33.9      | 3.45 |
| Tanga et al. [146] | 2010  | Cameroon    | Likoko           | 460.1     |       |           |       |
| Tchouassi et al. [147] | 2012  | Ghana       | Kpone-on-sea      | 62.1      |       |           |       |
| Tchuinkam et al. [51] | 2010  | Cameroon    | Djutitsa, Dschang, Santchou | 0; 90.5  |       | 62.8      |       |
| Thompson et al. [148] | 1997  | Mozambique  | Maputo            | 20        |       |           |       |
| Trape and Zoulani [149] | 1997  | Congo       | Brazzaville       | 101       |       | 0.3       |       |
| Trape et al. [150] | 1992  | Senegal     | Pikine, Dakar     | 0.4       |       | 0.01      |       |
| Vercruysse [151] | 1981  | Senegal     | Pikine, Dakar     | 43        |       |           |       |
| Vercruysse [152] | 1985  | Senegal     | North Senegal     | 1.65      |       |           |       |
| Yadouleton et al. [12] | 2010  | Benin       | Cotonou, Parakou, Porto Novo | 102.2; 54.7; 83.95|       |           |       |
| Zogo et al. [153] | 2019  | Côte d'Ivoire | Korhogo          | 2.46      |       |           |       |
ziemanni, Anopheles marshallii, and Anopheles rufipes were reported, but in very low densities (Table 3). Great diversity and higher densities of species in rural areas compared to periurban and urban centres were recorded (Fig. 5). For instance, in the city of Yaoundé, it was common to find fewer than four species at the city centre whereas this number could rise up to ten species in the nearby rural settings.

Discussion
The present study is an update of previous reviews on urban malaria in sub-Saharan Africa [2–4, 29, 32, 33], it provides new data on malaria transmission pattern and anopheline species distribution. Urbanization is increasingly blamed of influencing the epidemiology and evolution of vector-borne diseases in sub-Saharan Africa. More than half of the world’s population now lives in towns or cities and it is projected that this number could rise to 75% by 2050 [34]. From the review it appears that, the Entomological Inoculation Rate (EIR) is highly heterogeneous in cities across the continent [18, 35, 36]. In many cities centre, malaria transmission is low or absent while others register high EIR estimates [11, 37]. The difference between cities could derive from the scale of urban development, population size and the magnitude of unplanned urbanization. Unplanned urbanization characterized by the colonization of lowland areas for habitat construction, poor drainage system in urban settings, the development of slums and spontaneous habitats and the practice of agriculture in the city centre was reported to deeply influence malaria transmission intensity [15, 38]. Although EIR estimates were always higher in rural and peri-urban settings compared to urban centres [2], it also appeared that, because of increase poverty in urban settings there are an increasing number of people exposed to malaria transmission risk. In the city of Libreville for instance, a high transmission rate was recorded in the city centre characterized by poor
housing, high population density, low socio-economic level and inadequate management of waste, compared to the periphery where the population had a high socio-economic level and good management infrastructure [39]. In the city of Yaoundé, where slum-like conditions are common across the city, malaria transmission was highly prevalent in both the city centre and the periphery [11]. The close association between malaria and the economic status of the household has been highlighted in different studies across the continent [4]. Additional factors including river overflowing, city landscape and seasonal variations were also found to influence the intensity and pattern of malaria transmission [14, 40]. Important differences were noted when comparing malaria transmission intensity in the city centre before and after 2003. The comparison of the two periods suggested an increase in malaria transmission intensity in urban settings across sub-Saharan Africa after 2003 [11, 13, 31, 39, 41]. Transmission estimates surpassing 50 infected bites/person/year were frequently reported in cities across Africa supporting the existence of high parasite reservoirs in urban settings including migrants coming from highly endemic rural settings or population moving from urban to rural settings which could be infecting mosquito populations [30, 37]. It is also possible that the introduction of new techniques for the detection of Plasmodium infections in mosquitoes, such as ELISA and PCR techniques which were not used before could have increased the EIR estimates [42–44]. These highly sensitive techniques were reported to overestimate the true infection rate after salivary gland dissection by 1.1 to 1.9 folds [45–48]. The use of new molecular techniques or genomic advances could be vital for malaria control and elimination in Africa and there is a need to promote the use of new techniques to improve malaria vector control and surveillance in Africa [49].

The study also indicated high diversity of the vectorial system in different cities [12, 50–53]. Yet members of An. gambiae complex were largely predominant in most urban settings [11, 14, 54, 55]. This is in conformity with these species capacities to adapt to anthropogenic and/or environmental changes and to feed exclusively on humans [56]. The preferential breeding habitats of species of the An. gambiae complex are temporary water

| Type of breeding site | West Africa | References | Central Africa | References | East Africa | References |
|-----------------------|-------------|------------|----------------|------------|------------|------------|
| Artificial            |             |            |                |            |            |            |
| Urban farms           | 10          | [12, 13, 18, 21, 26, 28, 154–157] | 4              | [27, 158–160] |
| Tyre tracks           | 4           | [18, 28, 161, 162] | 1              | [19] | 6          | [22, 158, 160, 163–165] |
| Drains/gutter         | 4           | [154, 159, 162, 166] | 4              | [19, 167–169] | 5          | [170, 158, 159, 164, 165] |
| Swimming pool         | 1           | [21]        | 4              | [22, 27, 159, 171] |
| Pools                 | 4           | [161, 162, 166, 172] | 1              | [168] | 5          | [160, 164, 165, 173, 174] |
| Polluted water        | 3           | [13, 18, 155] | 1              | [19] | 1          | [175] |
| Pipes                 | 1           | [13]        | 2              | [176, 177] |
| Dam                   | 1           | [155]       | 1              | [178] |
| Brick holes           | 1           | [155]       |                |            |            |            |
| Domestic containers   | 2           | [162, 166]  | 2              | [19, 168] | 3          | [163, 165, 179] |
| Footprint             | 2           | [19, 167]   | 2              | [163, 165] |
| Ditches/pts           | 1           | [154]       | 1              | [169] | 4          | [163–165, 174] |
| Rice paddies          | 1           | [180]       | 2              | [163, 165] |
| Puddles               | 1           | [154]       | 2              | [19, 169] | 4          | [159, 164, 173] |
| Holes                 | 1           | [164]       | 1              | [164] |
| Canoes                | 2           | [168, 169]  |                |            |            |            |
| Total                 | 33          |            | 18             | [19] | 43         |            |
| Natural               |             |            |                |            |            |            |
| Swamps                | 3           | [28, 154, 155] | 1              | [19] | 4          | [159, 160, 163, 164] |
| Streams/rivers/lagoon | 6           | [21, 154, 156, 161, 32, 181] | 1              | [182] | 3          | [159, 164, 173] |
| Ponds                 | 1           | [161]       | 2              | [178, 183] | 1          | [159] |
| Well                  | 1           | [13]        | 1              | [168] |
| Ground water/springs  | 2           |            |                |            | 2          | [27, 158] |
| Tree holes            | 2           | [166, 168]  | 1              | [184] |
| Clay soil             | 1           | [21]        | 1              | [27] |
| Flood plain/ravine    | 1           | [155]       |                |            | 1          | [171] |
| Total                 | 13          | 7           | 13             |            |            |            |
Table 3  Composition of anopheline species recorded in main cities across Africa

| Africa subregion | Country               | Cities                  | Main species (> 90% total)               | Others species < 10% | References |
|------------------|-----------------------|-------------------------|------------------------------------------|----------------------|------------|
| Central Africa   | Cameroon              | Garoua                  | An. gambiae s.s                          | An. rufipes/An. pharoensis/An. paludis | [145, 180, 52] |
|                  |                       | Yaoundé                 | An. gambiae s.s./An. coluzzii/An. funestus | An. nili/An.marshalli/An. ziemanni/An.moucheti | [1, 11, 19, 30, 37, 121, 185, 59, 186] |
|                  |                       | Douala                  | An. coluzzi                             | An. gambiæ s.s/An. ziemanni    | [14, 167, 168] |
| Gabon            |                       | Libreville              | An. gambiae s.s                         | An. melas/An. gambiæ s.s     | [11, 19, 30, 37, 121, 185, 59, 186] |
|                  |                       | Port-Gentil             | An. melas/An. gambiæ s.s               | An. melas/An. gambiæ s.s     | [96] |
|                  |                       | Franceville             | An. funestus/An. gambiæ s.s            | An. melas/An. gambiæ s.s     | [86] |
| Equatorial Guinea|                       | Bioko                   | An. funestus/An. gambiæ s.s            | An. melas                 | [13, 187–191] |
| Tchad            |                       | N’Djamena               | An. gambiæ s.s/An. arabiensis/An. coluzzi | An. melas/An. gambiæ s.s     | [192–194] |
| Angola           |                       | Lobito                  | An. coluzzi/An. gambiæ s.s             | An. melas                 | [195, 196] |
|                  |                       | Luanda                  | An. gambiæ s.s                         | An. melas                 | [197] |
| Congo            |                       | Brazzaville             | An. gambiæ s.s                         | An. melas                 | [149] |
| Democratic Republic of Congo | Lodja/Kapokowe | An. gambiæ s.s | An. gambiæ s.s/An. funestus/An. paludis | An. melas/An. gambiæ s.s     | [180, 183] |
|                  |                       | Kribi                   | An. gambiæ s.s/An. funestus/An. paludis | An. melas                 | [202] |
|                  |                       | Kibali                  | An. gambiæ s.s/An. funestus/An. paludis | An. melas                 | [206] |
| Central Africa Republic | Benin | Cotonou              | An. gambiæ s.l                          | An. pharoensis/An. ziemanni/An. funestus | [12] |
|                  |                       | Porto Novo              | An. gambiæ s.l                          | An. pharoensis/An. ziemanni/An. funestus | [12] |
| West Africa      |                       | Côte d’ivoire           | An. gambiæ s.l                          | An. funestus/An. funestus/An. melas | [207] |
|                  |                       | Yamoussoukro            | An. gambiæ s.l                          | An. funestus/An. funestus/An. melas | [207] |
|                  |                       | Abidjan                 | An. gambiæ s.s                         | An. funestus/An. funestus/An. melas | [208, 209] |
|                  |                       | Bouaké                  | An. gambiæ s.s                          | An. funestus/An. funestus/An. melas | [210] |
| Gambia           |                       | Bakau                   | An. arabiensis/An. coluzzii             | An. gambiæ s.s/An. gambiæ s.s/An. coluzzii hybrids | [211] |
| Senegal          |                       | Dakar                   | An. gambiæ s.l/An. arabiensis           | An. melas/An. pharoensis    | [212] |
|                  |                       | Kedougou                | An. coustani/An. funestus               | An. melas/An. pharoensis    | [212] |
| Guinea           |                       | Conakry                 | An. coluzzii/An. gambiæ s.s             | An. melas/An. pharoensis    | [54, 213, 214] |
|                  |                       | Siguiri                 | An. gambiæ s.s/An. funestus             | An. melas/An. pharoensis    | [215] |
| Guinea-Bissau    |                       | Bissau                  | An. gambiæ s.s/An. coluzzii/An. arabiensis | An. melas/An. pharoensis    | [216–220] |
| Mauritania       |                       | Nouakchott              | An. gambiæ s.s/An. arabiensis           | An. melas/An. pharoensis    | [221, 222] |
| Burkina Faso     |                       | Bobo-Dioulasso          | An. arabiensis                          | An. melas/An. pharoensis    | [223, 223–225] |
|                  |                       | Ouagadougou             | An. gambiæ s.l/An. coluzzii/An. arabiensis | An. melas/An. pharoensis    | [154, 226, 227] |
| Cabo-Verde       |                       | Praia                   | An. arabiensis                          | An. coluzzii/An. gambiæ s.s | [228, 229] |
| Liberia          |                       | Montserrado             | An. gambiæ s.s                          | An. coluzzii/An. gambiæ s.s | [230, 231] |
|                  |                       | Monrovia                | An. gambiæ s.s/An. coluzzii             | An. coluzzii/An. gambiæ s.s | [232] |
| Nigeria          |                       | Ilorin and Minna        | An. gambiæ s.s                          | An. melas/An. pharoensis    | [134] |
|                  |                       | Lagos                   | An. gambiæ s.s/An. arabiensis           | An. niveolorum/An. funestus | [233–236] |
|                  |                       | Bayelsa                 | An. gambiæ s.s                          | An. niveolorum/An. funestus | [83] |
| Mali             |                       | Bamako                  | An. coluzzii/An. gambiæ s.s             | An. arabiensis/An. coluzzii | [237–239] |
| Ghana            |                       | Accra                   | An. gambiæ s.s/An. coluzzii             | An. gambiæ s.s/An. coluzzii | [13, 170, 240] |
| Niger            |                       | Niamey                  | An. gambiæ s.s/An. arabiensis           | An. gambiæ s.s/An. coluzzii | [40] |
| Togo             |                       | Tessaoua                | An. coluzzii/An. gambiæ s.s             | An. melas/An. pharoensis/An. ziemanni | [194] |
|                  |                       | Lomé                    | An. gambiæ s.s/An. coluzzii             | An. melas/An. pharoensis/An. ziemanni | [241] |
collections exposed to sunlight. However, these species were reported to also breed in different types of habitats, including drains, septic tanks, artificial containers, standing water collection full of organic matters in urban settings [2, 15]. Moreover, it appears from the study that species composition could vary significantly between cities [51]. The following observation, highlights the influence of different factors genetic and tolerance level shaping the adaptation capacity of species in different environments [57, 58]. In the city of Yaoundé, the predominance of An. coluzzii over An. gambiae was attributed to the high tolerance of the species to organic pollutants, such as ammonia [59]. In coastal cities along the Atlantic Ocean, such as Libreville and Malabo, An. gambiae was found to be highly predominant whereas it was less abundant in Douala where An. coluzzii was the predominant species [60]. Explaining species distribution relying only on species specific data could be more complex as highlighted in a recent meta-analysis [61] and deserve further investigation. Urban agriculture coupled with uncontrolled disposal of containers to collect rainwater is creating an increasing number of favourable aquatic breeding habitats for Anopheles in urban cities. It has been reported that some Anopheles species are now adapting to this new environment, as described for An. stephensi, which breeds in man-made water containers, such as household water storage containers and garden reservoirs [24, 62]. The invasion of Africa by new species, such as An. stephensi, which is now found in many countries across East Africa such as Djibouti, Somalia, Sudan, and Ethiopia, could pose a great challenge for malaria elimination in Africa particularly in urban settings [1, 23, 63–65]. The invasion of Djibouti by Anopheles stephensi in 2012 was associated with a 30-fold increase in malaria cases, from 1684 in 2012 to 49,402 in 2019 [1]. Anopheles stephensi was also reported to display high resistance to pyrethroids, carbamates and organophosphates [64]. The species bites outdoors and displays a highly opportunistic behaviour feeding on both human and animals, a behaviour which could affect the efficiency of current control measures [64]. Some cities exhibited a high species diversity with three to six species commonly reported whereas low species diversity was recorded in others. This heterogeneity between cities could derive from difference in vegetation, altitude, urbanization level and seasons [66–70]. The presence of forest fringes as observed in the close neighbourhood of some cities [51] could increase the number of potential breeding sites exploited by mosquitoes and explain the diversity. Mosquitoes found in the urban environment are also exposed to a high selection pressure induce by the use of insecticide-treated nets, pollution, deforestation, anthropogenic changes and environmental changes which could reduce the diversity and distribution of species [15]. Indeed high intensity insecticide resistance affecting almost all insecticide families was

### Table 3 (continued)

| Africa subregion | Country     | Cities          | Main species (> 90% total)                           | Others species < 10%              | References |
|------------------|-------------|-----------------|-----------------------------------------------------|-----------------------------------|------------|
| Ethiopia         | Kebbi Dehar | An. stephensi   |                                                     |                                   | [23, 242]  |
|                  | Arjo-Didessa| An. arabiensis  | An. amharicus/An. coustani/An. pharoensis/An. funestus |                                   | [159, 243] |
| Djibouti         | Djibouti    | An. arabiensis/An. stephensi |                                   |                                   | [244, 245] |
| Sudan            | Khartoum    | An. arabiensis  |                                                     |                                   | [246–250]  |
| Tanzania         | Dar es Salaam | An. arabiensis | An. funestus/An. gambiae s.s./An. coustani         |                                   | [55, 251]  |
|                  | Morogoro    | An. arabiensis  | An. gambiae s.s./An. coustani/An. quadranulatus     |                                   | [162, 252] |
| East Africa      | Kenya       | Nairobi         | An. arabiensis/An. funestus                        | An. rivulorum/An. leeson, An. parensis/An. longipalpis/An. vaneedeni | [253, 254] |
|                  |             | Kisumu          | An. funestus                                       | An. rivulorum/An. leeson, An. parensis/An. longipalpis/An. vaneedeni | [255]      |
|                  |             | Kilifi          | An. funestus                                       | An. rivulorum/An. leeson, An. parensis/An. longipalpis/An. vaneedeni | [255, 256] |
|                  |             |                 |                                                     | An. funestus/An. ziemanni/An. coustani/An. mouchet/An. gambiae s.s. | [108, 257] |
|                  |             | Rwandan         | An. arabiensis                                     |                                   | [258]      |
|                  |             | Kigali          | An. arabiensis                                     | An. gambiae s.s                   | [259]      |
|                  |             | Kanzi           | An. demeilloni/An. arabiensis/An. funestus         |                                   |            |
|                  |             |                 |                                                     |                                   |            |
|                  |             | Tororo          | An. arabiensis                                     | An. gambiae s.s                   |            |

Reference:

[1] Doumbe-Belisse et al. Malar J. (2021) 20:364
reported in *An. gambiae s.l.* populations from most urban settings [12, 19, 71–73]. The rapid expansion of multiresistance pattern was reported to reduce bed nets efficacy in different epidemiological settings [74–76]. In urban settings where vector populations display resistance to insecticide, and outdoor feeding behaviour [11], the addition of targeted interventions such as larval control in hotspot areas could be keys for effective reduction of malaria transmission.

*Plasmodium falciparum* was the predominant malaria parasites recorded in almost all urban settings. This parasite is also the dominant species in rural settings [77]. Other species commonly found included *Plasmodium malariae* and *Plasmodium ovale* [53]. It is likely that the diversity of *Plasmodium* species in urban settings could be on the rise due to the intensification of travels between different regions of the globe. The exploration of factors favouring mosquito nuisance and malaria transmission in urban settings clearly shows the influence of urban expansion resulting from rapid population growth outpacing infrastructure development and highlight the need for further action by municipalities and public works services in the construction of drains or sewage systems to reduce breeding opportunities for mosquitoes [13].

**Conclusion**

The current review provides an update of the situation of malaria in urban settings in sub-Saharan Africa during the last decades. Although the risk of malaria transmission remains low in urban compared to rural settings, urban malaria is likely to increase as unplanned urbanization continues. Unplanned urbanization led to a proliferation of suitable breeding habitats for malaria vectors and thus increases the risk of exposition to mosquito bites and malaria transmission. To stop this trend in the disease burden, concerted actions need to be taken quickly at different levels to improve the management of malaria cases and control of vector populations. The development of integrated control approaches could be paramount for the effective control of vector-borne diseases in urban settings.

**Abbreviations**

EIRs: Entomological Inoculation Rate; PCR: Polymerase Chain Reaction; ELISA: Enzyme-Linked Immunosorbent Assay.

**Supplementary Information**

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**Additional file 1.** Database of the entomological inoculation rate estimates reported in the 90 scientific publications selected for the review.
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Authors’ contributions
Conceived and designed the study: CAN; performed the literature search: PDB, EK; interpreted, analysed data and wrote the paper: CAN, PDB, EK with the contributions of other authors; critically reviewed the manuscript: NCS, SNC, AT, LDDD, HPAA, CSW, FN. All authors read and approved the final manuscript.

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