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MINI-REVIEW

Resistance to insecticides in *Anopheles gambiae* complex in West Africa: A review of the current situation and the perspectives for malaria control

Abdou Azaque Zouré [1,2] · Athanase Badolo [3] · Frédéric Francis [1]

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Abstract
In West Africa, the *Anopheles gambiae sensu lato* (s.l.) complex mosquitoes are the main malaria vectors. Malaria control relies mainly on long-lasting insecticide-treated nets (LLINs) and to a lesser extent on indoor residual spray (IRS) of insecticides. Important progress has been made in terms of malaria morbidity and mortality in these past decades. Resistance to insecticides in *An. gambiae* s.l. was first attributed to their use in agriculture. Further, their use in public health increased selection pressure. Resistance has been recorded to the four main classes of insecticides used in public health in West Africa. However, the spread of insecticide resistance in West Africa is persistent due to the lack of management of resistance monitoring. Resistance to insecticides involves different mechanisms. Resistance to pyrethroids and organochlorines was caused by target modification such as some sodium channel mutations in addition to metabolic changes. Reduction of sensitivity to organophosphates and carbamates was caused by acetylcholinesterase mutations. Therefore, efforts should be made as quickly as possible to develop novel vector control techniques. Furthermore, it is also suggested to combine environmental, chemical, and biological management. In this review, we outline the insecticide resistance of *Anopheles* in West Africa and the current alternative tools for effective mosquito vector control.

Keywords Malaria · Insecticide resistance · Biological control-West Africa · *Anopheles gambiae*

Introduction

In West Africa, *An. gambiae* s.l. complex mosquitoes are the main malaria vectors (Darriet 2007; Dadzie et al. 2013). According to the *World Malaria Report 2018*, malaria is still a public health concern with an estimated 219 million cases of malaria occurred worldwide in 2017, compared with 217 million cases in 2016 and 239 million cases in 2010 (WHO 2018). The WHO (World Health Organization) African region is the most affected by malaria, whose most malaria cases (200 million or 92%) and accounted for 93% of malaria deaths in 2017 (WHO 2018). Several efforts for malaria control have been made in the last decade. Between 2000 and 2015, 17 countries worldwide (only two in Africa – Egypt and Morocco) eliminated malaria (zero indigenous cases for 3 years or more). Of these, only six countries worldwide, including only Morocco (in 2010) in Africa, have been certified as malaria-free by the WHO (2016).

The national malaria control programmes in sub-Saharan Africa rely mainly on long-lasting insecticide-treated nets (LLINs) and to a lesser extent on indoor residual spray (IRS) of insecticides for control of malaria (Ranson et al. 2011). The active ingredients of IRS formulations recommended by WHO belong to four insecticides classes: pyrethroids, organochlorines, organophosphates, and carbamates (WHO 2015a), whereas only pyrethroids are recommended as active

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ingredients of LLINs (Prato et al. 2012). The scaling up of insecticide-based measures for vector control coupled with artemisinin-based combination therapies (ACTs) have significantly reduced malaria mortality in sub-Saharan Africa (OMS 2014). The *World Malaria Report 2018* highlighted disparities in sub-Saharan Africa, with an increase in malaria morbidity of 3.5 million in 2017 compared to 2016 in the 10 most affected countries in sub-saharan Africa (WHO 2018). If low level and inadequacy of malaria investment is one of the main reason for this situation, the resistance of malaria vectors to insecticides has compromised the chance of these strategies to achieve successful malaria elimination (Ranson et al. 2009). WHO is targeting a 90% reduction of malaria cases and malaria mortality as part of the 2016–2030 pre-eradication agenda (WHO 2015b). Resistance to insecticides in malaria vectors was first linked to their use in agriculture (Diabate et al. 2002). Further, recent studies highlighted public health vector control tools including insecticide-treated bednets and insecticide spray as factors of selection pressure (WHO 2012). Nevertheless, resistance to insecticides is well established in malaria vector populations of West Africa. However, this insecticide resistance in *An. gambiae* s.l. has become a serious matter for malaria control and is a major challenge for malaria control programmes (Liu 2015). Resistance to carbamates and organophosphates has increased and may rise further in areas where IRS programmes have replaced pyrethroids with other active ingredients in response to a rise in resistance to pyrethroids (Ranson et al. 2011).

A systematic review of insecticide resistance of malaria vectors, *An. gambiae* s.l. complex mosquitoes, in countries in West Africa was performed, focussing on the mechanisms of malaria control in the region and their implications.

Status of insecticide resistance of malaria vectors in West Africa

Between 2007 and 2011, the distribution and use of LLINs and IRS increased significantly in West Africa (Coetzee and Koekemoer 2013). LLINs and IRS were effective against *An. gambiae* s.l., resulting in significant reductions in malaria transmission (WHO 2012) (Karunamoorthi and Sabesan 2013). Unfortunately, according to bioassays using the standard WHO protocol, resistance to all four classes of insecticide (pyrethroids, organophosphates, carbamates and organochlorines) has been reported in several countries of western Africa (Namountougou et al. 2012; WHO 2015a). *An. gambiae* s.l strains resistant to DDT was recorded in several countries of West Africa mainly due to its use in agriculture (Ranson et al. 2009) (Table 1).

In Benin, studies showed high levels of permethrin resistance in an agricultural area and an urban area (Djouaka et al. 2008). In southern Benin, strong resistance to permethrin and DDT was found in *An. gambiae* s.l, which might be due to L1014F kdr (Yadouleton et al. 2010) (Djègbè et al. 2011). Deltamethrin resistance was widespread and significant increase in CYP6P3, CYP6M2, GSTD3 expression was observed after a three-year implementation of LLINs (Yahouédo et al. 2016). In Burkina Faso, resistance to pyrethroids has increased in recent years (Toé et al. 2014) due to increased frequencies of 1014F kdr mutation and ace-1R (Badolo et al. 2012; Dabiré et al. 2014). In Ivory Coast, resistance to carbamates was detected in the 1990 and resistance to pyrethroids was first reported in 1993 (Edi et al. 2012). More recently, higher levels of resistance to pyrethroids, organochlorines, and carbamates (Zoh et al. 2018) and increased kdr and ace-1 gene frequencies were reported (Koffi et al. 2012).

In Gambia, two studies revelated 1014F kdr mutation was strongly associated with the first report to DDT resistance (Betson et al. 2009) and both DDT and deltamethrin resistance (Opondo et al. 2016).

In Ghana, resistance to pyrethroids, the most widespread insecticides in LLINs and IRS, is mostly linked with kdr mutation in *An. gambiae* s.s. (Baffour-Awuah et al. 2016). High resistance to pyrethroids, carbamates, and DDT, and high frequency of L119F-GSTe2 with A296S-RDL associed with upregulation of CYP6P9a, CYP6P9b, CYP6M7, and GSTe2 genes was observed (Riveron et al. 2016). In Guinea, resistance to all insecticides were associated with widespread L1014F kdr-west mutation and low levels of ace-1R mutation (Keita et al. 2017). In Liberia, resistance to deltamethrin but full susceptibility to bendiocarb (carbamate) and fenithrothion (organophosphate) was associated with high frequency of the 1014F kdr allele (Temu et al. 2012). Likewise, in Niger, susceptibility to bendiocarb and malathion (organophosphate) but resistance to pyrethroids and DDT was associated with L1014F kdr mutation (Soumaila et al. 2017).

In Mali, high levels of resistance to DDT, increased resistance to pyrethroids (deltamethrin and lambda-cyhalothrin) were associated with elevated metabolism of oxidase, glutathione S-transferases (GSTs), and esterase detoxification. Also, high frequencies of *kdr* and relatively low frequencies of *ace-1R* were found (Cisse et al. 2015; Keïta et al. 2016). In Nigeria, high resistance to organochlorines (DDT and dieldrin) and permethrin was reported (Oduola et al. 2012; Habibu et al. 2017) and was associated with L1014F and L1014S kdr mutations (Habibu et al. 2017), but full susceptibility to organophosphates and carbamates was found (Okorie et al. 2015). Furthermore, high frequencies of L119F-GSTe2 and dieldrin resistance were associated with A296S-RDL mutation (Djouaka et al. 2016b). In Senegal, widespread resistance to DDT and pyrethroids (Niang et al. 2016) was associated with high and widespread distribution of kdr-West L1014F mutation and low distribution of kdr-East L1014S mutation (Dia et al. 2018). Lambda-cyhalothrin resistance

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Table 1 Available insecticides and resistance level of the *Anopheles gambiae* in western Africa (2008–2018)

Countries	WHO susceptibility tests[1] Resistance level	Insecticide resistance report	Studies
Benin	-Permethrin 0.75% (PY), (S, R) -Deltamethrin 0.05% (PY), (R) -DDT 4% (OC), (R) -Bendiocarb 0.1% (C), (S, R) -Malthion 5% (OP), (S) -Deldrin 4% (OC), (S) -Propoxur 0.1% (C), (R, PR) -Pirimiphos methyl 0.25% (OP), (S) -Fenitrothion 1% (OP), (PR) -Carbosulfan 0.4%, (R) -Chlorpyrifos-methyl 0.4%, (R, PR, S)	-High levels of permethrin resistance in an agricultural area and an urban area -High levels of kdr-W mutation. -High levels of two P450s, CYP6P3, and CYP6M2 and significant increase of CYP6P3, CYP6M2 GSTD3 expression after a three-year implementation of LLINs. -Resistance to pyrethroids and DTT. -Increased frequency of kdr1014 F, 1014S, and 1575Y. -ace-1R at very low frequency (0.01%). -Low mortality to carbamates and organophosphates. -ace-1 mutation could not entirely explain resistance to carbamates and organophosphates. -Full susceptibility and strong resistance to bendiocarb. -Full susceptibility to chlorpyrifos-methyl. -Low resistance to carbosulfan. -High resistance levels to permethrin. -ace-1 R mutation present in *An. gambiae s.s*, but absent in *An. coluzzii*. -High deltamethrin resistance, suspected resistance to bendiocarb and susceptible to pirimiphos methyl and fenitrothion. -Widespread deltamethrin resistance.	(Djouaka et al. 2008; Djogbénou et al. 2011; Aïzoun et al. 2013; Padonou et al. 2012; Djègbè et al. 2014; Aïkpon et al. 2014 ; Sovi et al. 2014; Gnanguenon et al. 2015; Yahouédo et al. 2016)
Burkina Faso	-Permethrin 0.75%, (R, RP) -Deltamethrin 0.05% (PY), (R, PR) -Bendiocarb 0.1%, (PR, R, S) -Fenithrothion 0.05%, (PR) -DDT 4% (OC), (R, PR) -Fenitrothion 1% (OP), (PR, S)	-Multiple insecticide resistance in rice growing area. -Pyrethroid resistance increased in intensity in recent years. -Resistance to DDT and pyrethroids in the south-west of Burkina. -Resistance of DDT and permethrin in all four sites (Goundry, Koupela, Kuinima, Soumousso). -Carbamate and organophosphate resistance relatively rare and largely confined to the south-west. -Low resistance to bendiocarb in *An. gambiae* s.s. but not in *An. coluzzii*. -High kdr mutation (L1014F) (0.92%) in *An. gambiae* s.s. -Increased of frequency of kdr L1014 F mutation in *An. gambiae s.s* and spread in *An. coluzzii*. -*ace-1R* mutation prevailed predominately in *An. gambiae s.s*. -Moderate frequency of ace-1R mutation in the Sudan and Sudan-Sahel regions and absent in the Sahel region. -Detection of GABA V327I mutations. -First report of Ace.1G119S mutation in *An. arabiensis*. -ace-1R mutation in both *An. coluzzii*. (0.04 to 0.13) and *An. gambiae* s.s. (0.25 to 0.5), but absent in *An. arabiensis*.	(Dabiré et al. 2008; Djogbénou et al. 2008; Badolo et al. 2012; Namountougou et al. 2012; Dabiré et al. 2009, 2012, 2014; Toé et al. 2014)
Ivory Coast	-Permethrin 0.75%, (R, PR) -Deltamethrin 0.05%, (R, PR, S) -Alpha-cyperméthrin 0.05%, (R) -Lambda-cyhalothrin 0.05%), (R) -DDT 4%, (R) -α-cypermethrin 0.05%, -Pirimiphos-methyl 1% -Bendiocarb 0.1%, (PR, R) -Malathion 5%, (S) -Carbosulfan 0.4% (C), (R) -Propoxur 0.4% (C), (R) -Chlorpyrifos-methyl 0.4% (OP), (PR, S) -Fenitrothion 1% (OP), (R, PR, S) -Alphacyperméthrine (0.1%), (RP)	-Resistance to all insecticide classes. -High resistance levels to pyrethroids, organochlorines, and carbamates were widespread. -Various levels of resistance to pyrethroids (deltamethrin, permethrin, and lambda-cyhalothrin). -Strongly resistant to deltamethrin, bendiocarb, and DDT. -Probable resistance to malathion. -Elevated activity of insecticide detoxifying enzymes (esterases and glutathione S-transferases [GSTs]). -Resistance to carbosulfan and propoxur. -Suspected resistance to chlorpyrifos-methyl. -Low resistance to fenitrothion. -Frequency of L1014F kdr mutation varied from 0.37 in the site without agricultural insecticide to 0.95 in the site with intense use of insecticides. -High frequency of kdr L1014F (91%-96%). -High allelic frequencies of kdr L1014F mutation in *An. gambiae s.s.* (85.9–99.8%) and *An. coluzzii* (81.7–99.6%). -Low frequencies of ace-1R (below 0.5%) in *An. gambiae s.s.* (25.6–38.8%) and *An. coluzzii* (28.6–36.7%). -First report of the East African 1014S kdr mutation. -G119S mutation in both *An. coluzzii* and *An. gambiae* s.s. -High resistance to pyrethroids, DDT, and carbamates. -First detection of N1575Y mutation in resistance to pyrethroids. -L1014F kdr (0.33 in 2012 compared to 0.05 in 2002). -Resistance to pyrethroids and DDT.	(Ahoua Alou et al. 2010; Konan et al. 2011); Edi et al. 2012) ;Koffi et al. 2012); Ahoua Alou et al. 2012; Tia et al. 2017); Chouaïbou et al. 2017; Edi et al. 2017; Sadia-Kacou et al. 2017; Zoh et al. 2018; Camara et al. 2018)
Gambia	-Deltamethrin 0.05%, (R, RP) -DDT 4%, (R, RP) -Permethrin 0.75% (PY) (PR)	-Resistance to DT and deltamethrin. -1014F kdr mutation strongly associated with both DDT and deltamethrin. -First report of DDT resistance.	(Betson et al. 2009; Opondo et al. 2016)

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Table 1 (continued)

Countries	WHO susceptibility tests[1] Resistance level	Insecticide resistance report	Studies
		-Suspected resistance to permethrin and deltamethrin.	
Ghana	-Propoxur 0.1% (C), (R) -Bendiocarb 0.1% (C), (R) -Cyfluthrin 0.15% (PY), (R, S) -Deltamethrin 0.05% (PY), (R, S) -Lambda-cyhalothrin 0.05% (PY), (R, S) -Pirimiphos-methyl 0.25% (OP), (S) -Permethrin 0.75% (PY), (R) -DDT 4% (OC), (R) -Dieldrin 4% (OC), (R) -Malathion 5% (OP), (S)鳥-Etofenprox 0.5% (R)	-Resistance to all classes of insecticides except organophosphates. -Organophosphates are considered appropriate for IRS. -Highest level of resistance to pyrethroids. -Lowest knockdown resistance mutant gene. -Higher frequency of ace-1 119S in *An. gambiae s.s* than *An. coluzzii*, exceeding 90%. -ace-1 G119S strongly associated with resistance. -High frequency of L119F-GSTe2 and A296S-RDL. -Upregulation of CYP6P9a, CYP6P9b, CYP6M7, and GSTe2 genes. -High resistance to pyrethroids, carbamates, and DDT.	(Anto et al. 2009) (Essandoh et al. 2013; Baffour-Awuah et al. 2016; Riveron et al. 2016; Dery et al. 2016)
Guinea	-Deltamethrin 0.05%, (R) -Permethrin 0.75%, (R) -Alphacypermethrin 0.1%, (R) -Lambda-cyhalothrin 0.05%, (R) -DDT 4%, (R) -Bendiocarb 0.1%, (R)	-Resistance to all insecticides (deltamethrin, permethrin, alphacypermethrin, lambda-cyhalothrin, DDT, and bendiocarb) -kdr-west mutation (60% or more) was widespread. -Low levels of ace-1R mutation.	(Keita et al. 2017)
Liberia	-Deltamethrin 0.05%, (R) -Bendiocarb 0.1%, (S) -Fenithrothion 0.05%,(S)	-Resistance to deltamethrin but full susceptibility to bendiocarb and fenithrothion. -High frequency of the 1014F kdr allele (90.5%).	(Temu et al. 2012)
Mali	-Lambda-cyhalothrin 0.05%, (R, RP) -DDT 4%, (R, RP) -Permethrin 0.75%, (R, RP) -Deltamethrin 0.05%, (R, RP) -Bendiocarb 0.1%, (S) -Fenitrothion 1.0%, (S)	-Susceptible but suspected resistance.鳥-High levels of resistance to DDT. -Increased resistance to deltamethrin and lambda-cyhalothrin. -Low resistance to fenitrothion and bendiocarb. -High allelic frequencies of *kdr* in all sites. -Relatively low allelic frequencies of *ace-1R*. -Elevated insecticide metabolism of oxidase, GSTs, and esterase detoxification.	(Cisse et al. 2015; Keïta et al. 2016)
Niger	-Permethrin 0.75%, (R) -Deltamethrin 0.05%, (R, RP) -Lambda-cyhalothrin 0.05%, (R, RP) -Etofenprox 0.5%, (R, RP) -Alpha-cypermethrin 0.05%, (R) -DDT 4%, (R)鳥-Bendiocarb 0.1%, (S) -Malathion 5%, (S)	-Susceptible to bendiocarb and malathion but resistant to pyrethroids and DDT. -L1014F kdr mutation present (frequency of 58%).	(Soumaila et al. 2017)
Nigeria	-Dieldrin 4% (OC), (R) -DDT 4% (OC), (R) -Permethrin 0.75% (PY), (R) -Deltamethrin 0.05% (PY), (PR) -Bendiocarb 0.1% (C), (PR) -Malathion 5%, (S) -Lambda-cyhalothrin 0.05%, (R) -Cyfluthrin 0.15% ,(S) -Etofenprox 0.5%, (R)	-Very low resistance to deltamethrin and propoxur. -High resistance to DDT. -High frequencies allelic kdr-west mutation. -Absence of ace-1R point mutation in population resistant to carbamates. -High resistance to DDT and permethrin. -Suspected resistance to bendiocarb. -Insecticide resistance associated with L1014F and L1014S kdr mutations. -Resistance to pyrethroids and DDT but full susceptibility to organophosphates and carbamates. -1014F kdr detected at a frequency of 5.8%-24.52%.	(Oduola et al. 2012; Okorie et al. 2015; Habibu et al. 2017)
Senegal	-Permethrin 0.75%, (R) -Deltamethrin 0.05%, (RP, S) -Lambda-cyhalothrin 0.05%, (R) -DDT 4%, (R) -Bendiocarb 0.1%, (S) -Malathion 5%, (S)	-High frequence of kdr-West L1014F mutation (89.53%). -Low of kdr-East L1014S (10.24%). -Widespread resistance to DDT and pyrethroids. -Widespread distribution of the 1014F kdr.	(Niang et al. 2016; Dia et al. 2018)
Togo	-Permethrin 0.75%, (R) -DDT 4%, (R)	-First report of L1014S kdr (66–100%). -High resistance to DDT and permethrin. -kdr N1575Y frequency was 10–45%. -ace-1 G119S frequency was 4–16%.	(Djègbè et al. 2018)

[1] OC, organochlorines; OP, organophosphates; C, carbamates; PY, pyrethroids; WHO: World Health Organisation

According to WHO recommendations, 98–100% mosquito mortality indicates full susceptibility (S), 80–97% indicates potential resistance (PR) that needs to be confirmed, and < 80% mortality indicates resistance (R) (MR4 2014)

This table shows that resistance to all four classes of insecticides (organochlorines, pyrethroids, organophosphate, and carbamate) used in LLINs and IRS has increased from 2008 to 2018 in West Africa. The mechanisms of metabolic resistance and target site resistance have been investigated in these studies

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was mostly conferred by overexpressed CYP6M7 (Samb et al. 2016). In Togo, strains that were highly resistant to DDT and permethrin were observed with high frequencies L1014S kdr N1575Y (Djègbè et al. 2018).

Despite this resistance, populations susceptibe to organophosphates still exist (Coetzee and Koekemoer 2013). *An. gambiae* s.l were sensitive to pyrethroids until 2015 (Ranson and Lissenden 2016). **(**Table 1**)**. Therefore, before finding more viable alternatives, there is still the possibility of continuing to use insecticides through IRS and LLINs. But until when will this remain relevant?

Mechanisms involved in insecticide resistance

Target site resistance: mutations of ace-1, kdr, GABA, and GSTe2 genes

Resistance by target modification of *An. gambiae* includes mutations of acetylcholinesterase (AChE) and GABA receptors, voltage-gated sodium channels, and glutathione S-transferase epsilon 2 (GSTe2), and knockdown resistance (kdr) (Wondji et al. 2011; Platt et al. 2015). Several previous studies have been done on these mutations in western Africa and show that resistance is increasing.

Modification of acetylcholinesterase (ace-1)

Acetylcholinesterase (AChE), encoded by the ace-1 gene, is the target of organophosphates (OPs) and carbamates (Assogba et al. 2016). The G119S mutation has been associated with high levels of resistance to carbamates and orpganophosphates in *An. gambiae* s.l. (Assogba et al. 2014; Liebman et al. 2015) in West Africa. In 2012, multiple types of resistance with the concomitant presence of kdr L1014F and ace-1 G119S mutations in *An. gambiae* s.l. were found throughout Burkina Faso and most savannas of western Africa (Namountougou et al. 2012; Jones et al. 2012b). In Benin, the ace-1 mutation was less frequent (Yadouleton et al. 2010). At a larger scale, IRS could fade because this mutation is associated with resistance to only two (organophosphates and carbamate) of the four types of insecticides used in malaria control.

Modification of voltage-gated sodium channel (kdr)

The target of pyrethroids and organochlorine DDT is the voltage-gated sodium channel (VGSC**)** (Yang et al. 2016). A mutation of VGSC modifies its binding ability, resulting in knockdown resistance (kdr) (Karunamoorthi and Sabesan 2013). Four kdr mutations (L1014S, L1014P, L1014F, and N1575Y) are widely distributed in *An. gambiae* s.l. (Jones et al. 2012a). Previous studies showed that L1014F kdr was most widely distributed among *An. gambiae* s.l. populations in West Africa. Recently the L1014S kdr, which was initially predominant in East Africa, was reported also in West Africa, particularly in Benin and Burkina Faso (Jones et al. 2012a; Namountougou et al. 2012). The L1014P and N1575Y mutations were also frequently found in *An. gambiae* s.l. (Ranson et al. 2011; Jones et al. 2012a). After 2001–2003, the prevalence of L1014F mutations seems to have increase in *An. coluzzii* and *An. Arabiensis* (Knox et al. 2014; Baffour-Awuah et al. 2016), but was low frequency in *An. gambiae* s.s. (Djègbè et al. 2011; Dabiré et al. 2014). This mutation could greatly affect the implementation of LLINs because it only causes resistance to pyrethroids.

Modification of the GABA receptor (rdl)

The γ-aminobutyric acid (GABA) receptor encoded by the rdl gene is the target of cyclodienes, organochlorines (lindane), and phenylpyrazoles (fipronil) (Casida and Durkin 2015). A302G and A302S mutations were associated with dieldrin resistance in *An. gambiae* s.l (Wondji et al. 2011; Platt et al. 2015; Zhang et al. 2016). The V327I mutation associated with the A296S substitution in dieldrin resistance was detected in Burkina Faso and Benin (Coetzee and Koekemoer 2013; Djouaka et al. 2016a, b). This mutation was not yet widespread but strategies are still needed for its control. Due to resistance to organochlorines, the IRS may be non-operational.

Modification of glutathione S-transferase epsilon 2 (GSTe2)

The glutathione S-transferase gene, GSTe2, is implicated in resistance to the major classes of insecticides (mostly organophosphate and pyrethroids such as permethrin). The GSTe2 gene was found to be overexpressed in resistant strains of *An. gambiae* s.l. (Djadid et al. 2006; Djouaka et al. 2011). A single amino acid change L119F in upregulated GSTe2 confered high levels of metabolic resistance to DDT (Djouaka et al. 2016b). In Benin and Nigeria, mutation of the resistant allele L119F-GSTe2 was present at high frequencies and was also frequently associated with the A296S-RDL mutation responsible for dieldrin resistance (Riveron et al. 2014). Glutathione S-transferase overexpression and A296S-RDL once again compromise the implementation of IRS and LLINs.

Metabolic and behavioural resistance

Increased metabolism of the pyrethroid deltamethrin was linked with upregulation of cytochrome P450 CYP9K1 (Vontas et al. 2018). Also, the cytochrome P450 genes (CYP4G), especially CYP4G16 and CYP4G17, were overexpressed in resistant strains of *An. gambiae* s.l., suggesting a possible link with cuticular-based resistance (Bass and

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Jones 2016). Also, the cytochrome P450 monooxygenases, GSTs, and carboxylesterases (COEs) were responsible for metabolically based resistance to pyrethroids (PYs), organophosphates (OPs), organochlorines (OCs), and carbamates (Cs) (Prato et al. 2012; Baldet et al. 2014). Behavioural resistance was observed to DDT and permethrin. Exophily after IRS decreased, which suggested that mosquitoes were more likely to rest in houses with LLINs than in houses with IRS (Ossè et al. 2013). Increased exophagy (blood feeding outside of houses) by *An. gambiae* s.l. in response to LLINs has been reported in Kenya (Gatton et al. 2013).

Impact and management of insecticide resistance on malaria control

To measure the public health impact of insecticide resistance, it is critical to assess the changing malaria transmission dynamics in Africa and to mobilise resources against this resistance (Ranson and Lissenden 2016). In this context, new approaches to stop resistance are urgently needed (Ranson and Lissenden 2016; Churcher et al. 2016). The WHO Global Technical Strategy for Malaria Control 2016–2030 (GTS) target an elimination of malaria in at least 35 countries where there was transmission in 2015 (WHO 2015b). The goal of this strategy is, reduce malaria mortality rates at least 90% globally in 2030. The recommended package of core includes vector control, chemoprevention, diagnostic testing and treatment. Therefore, the best approach should be the development of integrated pest management (IPM) or integrated vector management (IVM) (Perveen 2011). These strategies aim to maintain the effectiveness of vector control despite the threat of resistance (Karunamoorthi and Sabesan 2013). Thus, this strategy could be an alternative for the effective management of insecticide resistance in West Africa. Then, control tools could integrate a combination of environmental management with physical, chemical, genetic, and biological controls, including entomophagous predators and entomopathogenic fungi (Bawin et al. 2015; Hemingway et al. 2016). Besides these proposals for innovative alternatives, countries in West Africa could synergise their efforts towards holistic management of malaria in this highly endemic region. This will allow early and coordinated responses to new resistance to limit it as much as possible as soon as possible.

Biocontrol using microorganisms

Use of entomopathogenic fungi

Entomopathogenic fungi such as *Metarhizium anisopliae* Metschn. and *Beauveria bassiana* (Bals.-Criv.) Vuill. have been advocated as biological control agents (Bawin et al. 2016). Recent studies have demonstrated the importance and potentiality of the combination of permethrin and entomopathogenic fungi as vector control interventions against insecticide resistant *An. gambiae* s.l. (Seye et al. 2014; Mohammed et al. 2015). Transgenic *M. pingshaense* can be used to manage *An. gambiae* s.l. resistant to pyrethroids (Bilgo et al. 2018a). Interestingly, insecticide resistant strains of *An. gambiae* s.l. were more susceptible to entomophathogenic fungi than insecticide susceptible strain of *An. gambiae* s.l. (Karunamoorthi and Sabesan 2013). Bawin et al. (2016) showed that three pathogenic fungal strains of fungi (namely: *Aspergillus clavatus* Desm, *Aspergillus flavus* Link, and *M. anisopliae*) may be productive and virulent against mosquito larvae. Toxins from *M. anisopliae* have different modes of action that improve the utility of entomopathogens as alternative malaria control tools (Bilgo et al. 2017). *Lagenidium giganteum* Couch (formerly: *L. culicidum*) is also pathogenic to mosquito larvae (Bawin et al. 2015). *Metarhizium* spp. hold promise for future applications in transgenic biological control of mosquitoes (Bilgo et al. 2018b). Development of *Beauveria bassiana s.l.* in *Anopheles* mosquitoes was observed after inoculation through tarsus and proboscis routes. Proboscis route of infection is critical for early death of vector mosquitoes (Ishii et al. 2017). All these fungi offer possibilities for diverse biopesticide formulations. However, their use in vector control is still limited to *Bacillus* crystals alone (Bawin et al. 2015). Substantial hurdles and limitations exist due to current technical platforms; hence, the experimentation and use of this method, which requires bioreactors, could be quite tedious for West African countries. Also, unfortunately, the formulation, storage, and shelf life of these entomopathogenic fungi for large-scale use is not as easy as for conventional neurotoxic chemicals.

Mosquito microbiota and paratransgenesis

The microbiota has an impact on different aspects of mosquito biology, which could be another strategy for malaria control (Hegde et al. 2015). The microbiota plays an important role in mosquito longevity, reproductive fitness, and reduced susceptibility to malaria parasites (Sharma et al. 2013). Antibiotics in ingested blood enhance *Plasmodium* infection status of *An. gambiae* by disturbing their gut microbiota (Gendrin et al. 2015). In mosquitoes, *Wolbachia* can cause vector sterility by cytoplasmic incompatibility and can also inhibit the transmission of protozoa (*Plasmodium*) (Slatko et al. 2014). *Wolbachia* was also found to inhibit *Plasmodium* development and stimulate an immune response in *An. gambiae* (Kambris et al. 2010). This evidence of the effects of *Wolbachia* promoted further investigations on the possible use of natural *Wolbachia-Anopheles* associations to limit malaria transmission (Baldini et al. 2014; Bourtzis et al. 2014). Often, the use of *Wolbachia* to reduce *Aedes* vectorial capacity and fitness has been successful (Slatko et al. 2014). This

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technology can be effectively transferred to *Anopheles* for malaria (Hemingway et al. 2016; Chavshin et al. 2014). *Enterobacter* was the predominant culturable gut bacterium that can block *P. falciparum* development (Cirimotich et al. 2011; Boissiere et al. 2012; Yadav et al. 2015). *Serratia* and *Asaia* interacted strongly with *Plasmodium* infection status and modified vector pathogenicity (Capone et al. 2013; Bando et al. 2013). Tchioffo et al. (2016) identified a correlation between the abundance of *Serratia* and *P. falciparum* infection both in the midgut and the salivary glands of mosquitoes. In addition, *Asaia* was found to act as an immune modulator of the expression of some anti-microbial peptides (AMPs), by releasing anti-*Plasmodium* effector molecules (Mitraka et al. 2013; Capone et al. 2013). Interestingly, in semi-field conditions, the application of transgenic *Asaia* as a tool for malaria control shows promising results (Mancini et al. 2016).

These first applications based on microbiota change pointed to the importance of characterising mosquito bacterial communities for paratransgenesis as an alternative approach to alter mosquito phenotype, which will block malaria transmission in malaria endemic areas such as in western Africa, as opposed to genetic modification of the insect itself (Tchioffo et al. 2016). Paratransgenesis in *Anopheles* was first described by Yoshida et al. (2001), who demonstrated that genetically modified *Escherichia coli* expressing a single-chain immunotoxin could reduce *Plasmodium berghei* oocyst development up to 58% in *An. stephensi* (Yoshida et al. 2001). Also, due to its worldwide ubiquity, *Pseudomonas* seemed to be another promising candidate for paratransgenesis to reduce and/or inhibit malaria transmission (Raharimalala et al. 2016).

However, some limitations need to be overcome. First, the field release of paratransgenic mosquitoes imposes a rigorous risk assessment framework coherent with a strict regulatory system appropriate to national and international guidelines. A thorough evaluation of the risks and benefits of this strategy is required. An investigation of hazards and safety related concerns is crucial (Mancini et al. 2016). Paratransgenesis could be applicable in western Africa, but first several studies to characterise the microbiota of *An. gambiae* in all agro-ecological areas will be needed to identify effector molecules and specific symbiotic bacteria refractory to *Plasmodium* in mosquitoes. More studies are needed to assess true effectiveness, risks, and benefits of paratransgenesis before general applications.

Bacteria used as insecticides

Bacillus thuringiensis serovar israelensis and *Lysinibacillus sphaericus* are two bacteria that act as larvicidal insecticides. They were successfully used in field conditions in Gambia and Ghana (Majambere et al. 2007; Nartey et al. 2013). *B. thuringiensis serovar israelensis* produces two different toxins encoded by crystal protein (Cry) (Cry4A, Cry4B, Cry11A, and Cyt1A) and Cyt genes. Both toxins were able to degrade the midgut membrane causing larval mortality (Lacey 2007). Similarly, *L. sphaericus* contains the insecticidal Mtx and Bin toxins, which paralyse the digestive system and disrupte the nervous system of mosquitoes (Bawin et al. 2016). Among biological insecticides, commercial formulations based on *B. thuringiensis* are the most sold (Bawin et al. 2015). Microorganisms produce various groups of biologically active compounds known as biosurfactants. Biosurfactants from *Bacillus subtilis* A1 and *Pseudomonas stutzeri* NA3 lead to various physiological changes in *An. stephensi*. This allows further consideration of their development as biopesticides in the fight against malaria (Parthipan et al. 2018). Limitations similar to that of for entomopathogenic fungi production exist. Lack of bioreactors could be a handicap in the implementation of bacteria to control malaria in western Africa. In addition, the other limitation could be that bacteria vitality in mosquitoes and related ecological environments cannot be fully controlled.

Plant-based insecticides

Nanoparticles: future trends

Nanoencapsulation is a process by which nanoparticles retain and slowly but efficiently release diverse molecules by diffusion, dissolution, and biodegradation (Khater 2012). Previous studies highlight that *Zornia diphylla* L. and *Nicandra physalodes* Schreb. processed as silver nanoparticles (AgNPs) are a promising and eco-friendly tool against vector mosquito larvae (Govindarajan et al. 2016b). AgNPs are easy to produce, cheap, stable over time, and can be employed at low dosages to strongly reduce vector mosquito larvae populations (Govindarajan et al. 2016a). Other studies investigated the biosynthesis of AgNPs using a cheap ethanol extract of *Artemisia vulgaris* leaves and *Hypnea musciformis* Wulfen (Murugan et al. 2015; Roni et al. 2015). Limitations of nanoencapsulation are its very high costs and adaptability to resources used by developing countries in malaria control.

Repellents and essential oils

Insect repellents can be a complement to the use of insecticides through application on the skin for individual protection where early bites of malaria vectors have occured. One of the widely used synthetic insect repellents is N,N-diethyl-meta-toluamide (DEET), which provides long-lasting protection of up to 8 h. Unfortunately, it has environmental and human health risks (Khater 2012). Most insect repellents are volatile terpenoids such as terpenen-4-ol. Today, the best-known repellent is citronella oil, which is obtained from various

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Cymbopogon species (Gramineae) as *C. nardus* (Ajaiyeoba et al. 2008).

Essential oils (EOs) may also act on mosquito larvae. The alkaloids isolated from *Annona squamosa* L. showed good larvicidal growth-regulating and chemosterilant abilities against *An. Stephensi* (Govil and Singh 2010; Khater 2012). Essential rhizome oil from *Curcuma longa* was found to be an efficient larvicide against *An. gambiae* (Solomon et al. 2012). Limonoids from neem oil and *Mentha piperita L.* oil may be an effective alternative to conventional synthetic insecticides for the control of *An. stephensi* (Govil and Singh 2010). EOs are volatiles with strong odour and soluble in organic solvents; they could be promising alternatives for malaria vector control. In tropical and Mediterranean countries, EOs are extracted from various aromatic plants generally by steam or hydrodistillation, and are an important part of the traditional pharmacopoeia (Govil and Singh 2010). EOs can also be synthesised by all plant organs and are found in several plant families. Some metabolites, such as monoterpenes (α-pinene, cineole, eugenol, limonene, terpinolene, citronellol, citronellal, camphor, and thymol) contribute to the repellent activity of essential oils (Nerio et al. 2010). β-caryophyllene, a sesquiterpene, is a repellent against *Aedes aegypti*. Phytol, a linear diterpene alcohol, is a repellent against *An. gambiae* (Price and Berry 2006; Govil and Singh 2010). Neem effects insects in several ways, including through feeding and oviposition deterrence, growth inhibition, and fecundity and fitness reductions. It was found to be effective against mosquitoes, and was considered a potential eco-friendly pesticide (Nicoletti et al. 2011). In Nigeria, traditionally 13 plants were used as insecticides, namely *Azadirachta indica* A. Juss., *Cymbopogan citrates* DC. Stapf, *Ossimum gratisimum* L., *Ageratum conysoides* L., *Annona squamosa* L., *Hyptis suavecolens* L. Poit., *Tridax procumbens* L., *Citrus sinensis* L. Osbeck, *Lantana camara* L., *Solanum nigrum* L., *Ancardium occidentale* Limaneus, *Myrianthus arboreus* P. Beauv, and *Xylopia aethiopica* Dunal, and are effective against *An. gambiae* s.l. (Mohammed et al. 2015). *Lantana camara* L., *Hyptis suaveolens* Poit., *Ocimum canum* Sims., and *Hyptis spicigera* Lam. are natural and eco-friendly substances for the control of malaria vectors, and can be used as insecticides against malaria vectors resistant to pyrethroids (Wangrawa et al. 2015). *Lantana camara* L. showed higher effectiveness against *An. gambiae* adults, eggs, and larvae (Wangrawa et al. 2018). *Lantana camara* L. showed high oviposition deterrence in *An. gambiae* (Wangrawa et al. 2016). Since 2013, in Burkina Faso, an anti-mosquito soap (named Faso Soap) with repellent substances such as citronella and shea was tested. Faso Soap is based on microencapsulation technology. If sold at the price of an ordinary soap, 300 CFA francs or 50 cents euros, it will be accessible to the entire populations of poor countries, unlike current expensive antimalarial products (Niyondiko et al. 2013). Almost all these plants exist in West Africa. Reforestation programmes could make them easily available to large populations. Therefore, this method of control appears to be the most appropriate for lower income populations.

Biotechnological approaches

One of the biotechnological approaches is the "release of insects with dominant lethality" (RIDL). By releasing male transgenic mosquitoes carrying the dominant lethal gene, this approach introduces the expression of a dominant lethal gene in vector populations (Huang et al. 2017). It induces preferential breakdown of the X chromosome during male meiosis to get a bias of male gamete production (Benelli et al. 2016). Breakdown of the paternal X chromosome in *An. gambiae* prevents it from being transmitted to the next generation, resulting in fully fertile mosquito strains producing more than 95% male offspring (Galizi et al. 2014). A weekly release of 50 million sterile males permitted the elimination of the New World screwworm *Cochliomyia hominivorax* Coquerel in the United States (Huang et al. 2017). A daily release over a period of 12 days of several thousand sterile individuals reduced almost 99% of the indigenous population of *Culex quinquefasciatus* Say from a small island (< 1 km^2) in Florida (Bawin et al. 2015).

The sterile insect technique (SIT) is based on the mass release of males sterilised by radiation. The sterile males are unable to fertilise eggs, thereby reducing the mosquito population. The SIT has been developed to successfully target *Aedes aegypti* for the control of dengue, chikungunya, and Zika virus (Phuc et al. 2007; Huang et al. 2017). In contrast, these techniques are still at the stage of field study for *Anopheles spp*. (Huang et al. 2017).

The gene drive mechanism is positioned as a innovative strategy for the control of vectors. This mechanism uses selective pressure on a given gene of interest to modify its genetic transmission in a population. A recent laboratory study used a CRISPR-cas9 gene drive targeting the doublesex gene (Agdsx), which caused a complete population suppression in *An. gambiae* mosquitoes (Kyrou et al. 2018).

Genetic forcing is currently being used in experiments on malaria vectors in West and East Africa. Target Malaria (https://targetmalaria.org/where-we-operate/) is conducting an experiment on genetically modified mosquitoes in Burkina Faso, Mali, and Uganda (Benelli and Beier 2017), with the goal of reducing the *An. gambiae* population. The purpose of genetic forcing is to disseminate a genetic trait that forces the sex ratio in favour of males (Wilke et al. 2018). This method could be an alternative for control of malaria in western Africa. The limited vectorial capacity of mosquito populations by genetic manipulation appears promising but poses ethical and legal problems. Thus, civil society organisations

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fear that genetic forcing may become uncontrollable and have unintended consequences.

Conclusions

This review highlights the existance of insecticide resistance in *An. gambiae* s.l., the main vector of malaria in West Africa. This resistance must be continuously integrated in anti-vectorial campaigns against malaria. Control programmes must rely on the continuous monitoring of vector populations, taking into account any useful methods available, to measure the effectiveness of the fight. Therefore, a multidisciplinary approach that includes biological control techniques (focused on microbiote manipulation and transgenesis) as well as repellents and essential oils from indigenous vegetation of West Africa for malaria control is recommended as a potential alternative to synthetic insecticides. Unfortunately, the application of these new tools could be confronted with biological, technical, ethical and legal challenges.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests in the publication of this paper.

References

Ahoua Alou LP, Koffi AA, Adja MA et al (2010) Distribution of ace-1 R and resistance to carbamates and organophosphates in Anopheles gambiae ss populations from Côte d'Ivoire. Malar J 9:167

Ahoua Alou LP, Koffi AA, Adja MA et al (2012) Status of pyrethroid resistance in Anopheles gambiae s. s. M form prior to the scaling up of Long Lasting Insecticidal Nets (LLINs) in Adzopé, Eastern Côte d'Ivoire. Parasit Vectors 5:289. https://doi.org/10.1186/1756-3305-5-289

Aïkpon R, Sèzonlin M, Ossè R, Akogbéto M (2014) Evidence of multiple mechanisms providing carbamate and organophosphate resistance in field An. gambiae population from Atacora in Benin. Parasit Vectors 7:568

Aïzoun N, Aïkpon R, Gnanguenon V et al (2013) Status of organophosphate and carbamate resistance in Anopheles gambiae sensu lato from the south and north Benin, West Africa. Parasit Vectors 6:274

Ajaiyeoba EO, Sama W, Essien EE et al (2008) Larvicidal Activity of Turmerone-Rich Essential Oils of Curcuma longa. Leaf and Rhizome from Nigeria on Anopheles gambiae. Pharm Biol 46: 279–282. https://doi.org/10.1080/13880200701741138

Anto F, Asoala V, Anyorigiya T et al (2009) Insecticide resistance profiles for malaria vectors in the Kassena-Nankana district of Ghana. Malar J 8:81. https://doi.org/10.1186/1475-2875-8-81

Assogba BS, Djogbénou LS, Saizonou J et al (2014) Phenotypic effects of concomitant insensitive acetylcholinesterase (ace-1 R) and knockdown resistance (kdr R) in Anopheles gambiae: a hindrance for insecticide resistance management for malaria vector control. Parasit Vectors 7:548

Assogba BS, Milesi P, Djogbénou LS et al (2016) The ace-1 Locus Is amplified in all resistant Anopheles gambiae mosquitoes: Fitness consequences of homogeneous and heterogeneous duplications. PLoS Biol 14:e2000618. https://doi.org/10.1371/journal.pbio.2000618

Badolo A, Traore A, Jones CM et al (2012) Three years of insecticide resistance monitoring in Anopheles gambiae in Burkina Faso: resistance on the rise? Malar J 11:232. https://doi.org/10.1186/1475-2875-11-232 doi

Baffour-Awuah S, Annan AA, Maiga-Ascofare O et al (2016) Insecticide resistance in malaria vectors in Kumasi, Ghana. Parasit Vectors 9: 633. https://doi.org/10.1186/s13071-016-1923-5

Baldet T, DARRIET F, David J-M et al (2014) Utilisation des insecticides et gestion de la résistance. Centre national d'Expertise sur les Vecteurs., Rennes

Baldini F, Segata N, Pompon J et al (2014) Evidence of natural Wolbachia infections in field populations of Anopheles gambiae. Nat Commun 5:3985. https://doi.org/10.1038/ncomms4985

Bando H, Okado K, Guelbeogo WM et al (2013) Intra-specific diversity of Serratia marcescens in Anopheles mosquito midgut defines Plasmodium transmission capacity. Sci Rep 3:1–9. https://doi.org/10.1038/srep01641

Bass C, Jones CM (2016) Mosquitoes boost body armor to resist insecticide attack. Proc Natl Acad Sci 113:9145–9147. https://doi.org/10.1073/pnas.1610992113

Bawin T, Seye F, Boukraa S et al (2015) La lutte contre les moustiques (Diptera: Culicidae): diversité des approches et application du contrôle biologique. Can Entomol 147:476–500. https://doi.org/10.4039/tce.2014.56

Bawin T, Seye F, Boukraa S et al (2016) Production of two entomopathogenic Aspergillus species and insecticidal activity against the mosquito Culex quinquefasciatus compared to Metarhizium anisopliae. Biocontrol Sci Technol 26:617–629. https://doi.org/10.1080/09583157.2015.1134767

Benelli G, Beier JC (2017) Current vector control challenges in the fight against malaria. Acta Trop 174:91–96. https://doi.org/10.1016/j.actatropica.2017.06.028

Benelli G, Jeffries C, Walker T (2016) Biological control of mosquito vectors: past, present, and future. Insects 7:52. https://doi.org/10.3390/insects7040052

Betson M, Jawara M, Awolola TS (2009) Status of insecticide susceptibility in Anopheles gambiae s.l. from malaria surveillance sites in The Gambia. Malar J 8:187. https://doi.org/10.1186/1475-2875-8-187

Bilgo E, Lovett B, Bayili K et al (2018a) Transgenic Metarhizium pingshaense synergistically ameliorates pyrethroid-resistance in wild-caught, malaria-vector mosquitoes. PloS One 13:e0203529

Bilgo E, Lovett B, Fang W et al (2017) Improved efficacy of an arthropod toxin expressing fungus against insecticide-resistant malaria-vector mosquitoes. Sci Rep 7:3433. https://doi.org/10.1038/s41598-017-03399-0

Bilgo E, Lovett B, St. Leger RJ et al (2018) Native entomopathogenic Metarhizium spp. from Burkina Faso and their virulence against the malaria vector Anopheles coluzzii and non-target insects. Parasit Vectors 11:209. https://doi.org/10.1186/s13071-018-2796-6

Boissiere A, Tchioffo MT, Bachar D et al (2012) Midgut microbiota of the malaria mosquito vector Anopheles gambiae and interactions with Plasmodium falciparum infection. PLoS Pathog 8:e1002742. https://doi.org/10.1371/journal.ppat.1002742

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Bourtzis K, Dobson SL, Xi Z et al (2014) Harnessing mosquito-Wolbachia symbiosis for vector and disease control. Acta Trop 132:S150–S163. https://doi.org/10.1016/j.actatropica.2013.11.004

Camara S, Koffi AA, Ahoua Alou LP et al (2018) Mapping insecticide resistance in Anopheles gambiae (s.l.) from Côte d'Ivoire. Parasit Vectors 11:19. https://doi.org/10.1186/s13071-017-2546-1

Capone A, Ricci I, Damiani C et al (2013) Interactions between Asaia, Plasmodium and Anopheles: New insights into mosquito symbiosis and implications in Malaria Symbiotic Control. Parasit Vectors 6:1. https://doi.org/10.1186/1756-3305-6-182

Casida JE, Durkin KA (2015) Novel GABA receptor pesticide targets. Pestic Biochem Physiol 121:22–30. https://doi.org/10.1016/j.pestbp.2014.11.006

Chavshin AR, Oshaghi MA, Vatandoost H et al (2014) Isolation and identification of culturable bacteria from wild Anopheles culicifacies, a first step in a paratransgenesis approach. Parasit Vectors 7:1–8. https://doi.org/10.1186/1756-3305-7-419

Chouaïbou M, Kouadio FB, Tia E, Djogbenou L (2017) First report of the East African kdr mutation in an Anopheles gambiae mosquito in Côte d'Ivoire. Wellcome Open Res 2:1–8. https://doi.org/10.12688/wellcomeopenres.10662.1

Churcher TS, Lissenden N, Griffin JT et al (2016) The impact of pyrethroid resistance on the efficacy and effectiveness of bednets for malaria control in Africa. Elife 5:e16090

Cirimotich CM, Dong Y, Clayton AM et al (2011) Natural microbe-mediated refractoriness to plasmodium infection in Anopheles gambiae. Science 332:855–858. https://doi.org/10.1126/science.1201618

Cisse MBM, Keita C, Dicko A et al (2015) Characterizing the insecticide resistance of Anopheles gambiae in Mali. Malar J 14:327. https://doi.org/10.1186/s12936-015-0847-4

Coetzee M, Koekemoer LL (2013) Molecular systematics and insecticide resistance in the major African malaria vector *Anopheles funestus*. Annu Rev Entomol 58:393–412. https://doi.org/10.1146/annurev-ento-120811-153628

Dabiré KR, Diabaté A, Djogbenou L et al (2008) Dynamics of multiple insecticide resistance in the malaria vector Anopheles gambiae in a rice growing area in South-Western Burkina Faso. Malar J 7:1–9. https://doi.org/10.1186/1475-2875-7-188

Dabiré KR, Diabaté A, Namontougou M et al (2009) Distribution of insensitive acetylcholinesterase (ace-1R) in Anopheles gambiae s.l. populations from Burkina Faso (West Africa). Trop Med Int Health 14:396–403. https://doi.org/10.1111/j.1365-3156.2009.02243.x

Dabiré RK, Namountougou M, Diabaté A et al (2014) Distribution and frequency of kdr mutations within Anopheles gambiae sl populations and first report of the ace. 1 G119S mutation in Anopheles arabiensis from Burkina Faso (West Africa). PloS One 9:e101484

Dabiré RK, Namountougou M, Sawadogo SP et al (2012) Population dynamics of Anopheles gambiae sl in Bobo-Dioulasso city: bionomics, infection rate and susceptibility to insecticides. Parasit Vectors 5:127

Dadzie SK, Brenyah R, Appawu MA (2013) Role of species composition in malaria transmission by the Anopheles funestus group (Diptera: Culicidae) in Ghana. J Vector Ecol 38:105–110

Darriet F (2007) Moustiquaires imprégnées et résistance des moustiques aux insecticides, IRD Éditions. IRD éd., Paris

Dery DB, Segbaya S, Asoalla V et al (2016) Anopheles gambiae (Diptera: Culicidae) Susceptibility to Insecticides and Knockdown Resistance Genes Prior to Introduction of Indoor Residual Spraying in 11 Districts in Ghana. J Med Entomol 53:1403–1409. https://doi.org/10.1093/jme/tjw098

Dia AK, Guèye OK, Niang EA et al (2018) Insecticide resistance in Anopheles arabiensis populations from Dakar and its suburbs: role of target site and metabolic resistance mechanisms. Malar J 17. https://doi.org/10.1186/s12936-018-2269-6

Diabate A, Baldet T, Chandre F et al (2002) The role of agricultural use of insecticides in resistance to pyrethroids in Anopheles gambiae sl in Burkina Faso. Am J Trop Med Hyg 67:617–622

Djadid ND, Barjesteh H, Raeisi A et al (2006) Identification, sequence analysis, and comparative study on GSTe2 insecticide resistance gene in three main world malaria vectors: Anopheles stephensi, Anopheles culicifacies, and Anopheles fluviatilis. J Med Entomol 43:1171–1177. https://doi.org/10.1603/0022-2585(2006)43[1171:ISAACS]2.0.CO;2

Djègbè I, Agossa FR, Jones CM et al (2014) Molecular characterization of DDT resistance in Anopheles gambiae from Benin. Parasit Vectors 7:409

Djègbè I, Akoton R, Tchigossou G et al (2018) First report of the presence of L1014S Knockdown-resistance mutation in Anopheles gambiae s.s and Anopheles coluzzii from Togo, West Africa. Wellcome Open Res 3:1–13. https://doi.org/10.12688/wellcomeopenres.13888.1

Djègbè I, Boussari O, Sidick A et al (2011) Dynamics of insecticide resistance in malaria vectors in Benin: first evidence of the presence of L1014S kdr mutation in Anopheles gambiae from West Africa. Malar J 10:261

Djogbénou L, Dabiré R, Diabaté A et al (2008) Identification and geographic distribution of the ACE-1R mutation in the malaria vector Anopheles gambiae in south-western Burkina Faso, West Africa. Am J Trop Med Hyg 78:298–302

Djogbénou L, Pasteur N, AkogbéTo M et al (2011) Insecticide resistance in the Anopheles gambiae complex in Benin: a nationwide survey. Med Vet Entomol 25:256–267. https://doi.org/10.1111/j.1365-2915.2010.00925.x

Djouaka R, Irving H, Tukur Z, Wondji CS (2011) Exploring mechanisms of multiple insecticide resistance in a population of the malaria vector Anopheles funestus in Benin. PLoS ONE 6:e27760. https://doi.org/10.1371/journal.pone.0027760

Djouaka R, Riveron JM, Yessoufou A et al (2016a) Multiple insecticide resistance in an infected population of the malaria vector Anopheles funestus in Benin. Parasit Vectors 9:453. https://doi.org/10.1186/s13071-016-1723-y

Djouaka RF, Bakare AA, Coulibaly ON et al (2008) Expression of the cytochrome P450s, CYP6P3 and CYP6M2 are significantly elevated in multiple pyrethroid resistant populations of Anopheles gambiae s.s. from Southern Benin and Nigeria. BMC Genom 9:538. https://doi.org/10.1186/1471-2164-9-538

Djouaka RJ, Atoyebi SM, Tchigossou GM et al (2016b) Evidence of a multiple insecticide resistance in the malaria vector Anopheles funestus in South West Nigeria. Malar J 15:. https://doi.org/10.1186/s12936-016-1615-9

Edi AVC, N'Dri BP, Chouaibou M et al (2017) First detection of N1575Y mutation in pyrethroid resistant Anopheles gambiae in Southern Côte d'Ivoire. Wellcome Open Res 2:71

Edi CVA, Koudou BG, Jones CM et al (2012) Multiple-Insecticide Resistance in *Anopheles gambiae* Mosquitoes, Southern Côte d'Ivoire. Emerg Infect Dis 18:1508–1511. https://doi.org/10.3201/eid1809.120262

Essandoh J, Yawson AE, Weetman D (2013) Acetylcholinesterase (Ace-1) target site mutation 119S is strongly diagnostic of carbamate and organophosphate resistance in Anopheles gambiae ss and Anopheles coluzzii across southern Ghana. Malar J 12:404

Galizi R, Doyle LA, Menichelli M et al (2014) A synthetic sex ratio distortion system for the control of the human malaria mosquito. Nat Commun 5:3977. https://doi.org/10.1038/ncomms4977

Gatton ML, Chitnis N, Churcher T et al (2013) The importance of mosqiito behavioural adaptations to malaria control in Africa: mosquito behavioral adaptation to malaria control. Evolution 67:1218–1230. https://doi.org/10.1111/evo.12063

Gendrin M, Rodgers FH, Yerbanga RS et al (2015) Antibiotics in ingested human blood affect the mosquito microbiota and capacity

Author's personal copy

to transmit malaria. Nat Commun 6:1–7. https://doi.org/10.1038/ncomms6921

Gnanguenon V, Agossa FR, Badirou K et al (2015) Malaria vectors resistance to insecticides in Benin: current trends and mechanisms involved. Parasit Vectors 8:223. https://doi.org/10.1186/s13071-015-0833-2

Govil JN, Singh VK (eds) (2010) Recent progress in medicinal plants, vol 26: Cumulative index to abstracts, vols 1–25. Studium Press LLC, Houston

Govindarajan M, Khater HF, Panneerselvam C, Benelli G (2016a) One-pot fabrication of silver nanocrystals using Nicandra physalodes: A novel route for mosquito vector control with moderate toxicity on non-target water bugs. Res Vet Sci 107:95–101. https://doi.org/10.1016/j.rvsc.2016.05.017

Govindarajan M, Rajeswary M, Muthukumaran U et al (2016b) Single-step biosynthesis and characterization of silver nanoparticles using Zornia diphylla leaves: A potent eco-friendly tool against malaria and arbovirus vectors. J Photochem Photobiol B 161:482–489. https://doi.org/10.1016/j.jphotobiol.2016.06.016

Habibu UA, Yayo AM, Yusuf YD (2017) Susceptibility status of Anopheles gambiae complex to Insecticides commonly used for malaria control in northern Nigeria. Int J Sci Technol Res 6:47–54

Hegde S, Rasgon JL, Hughes GL (2015) The microbiome modulates arbovirus transmission in mosquitoes. Curr Opin Virol 15:97–102. https://doi.org/10.1016/j.coviro.2015.08.011

Hemingway J, Shretta R, Wells TNC et al (2016) Tools and strategies for malaria control and elimination: What do we need to achieve a grand convergence in malaria? PLoS Biol 14:e1002380. https://doi.org/10.1371/journal.pbio.1002380

Huang Y-J, Higgs S, Vanlandingham D (2017) Biological control strategies for mosquito vectors of Arboviruses. Insects 8:21. https://doi.org/10.3390/insects8010021

Ishii M, Kanuka H, Badolo A et al (2017) Proboscis infection route of Beauveria bassiana triggers early death of Anopheles mosquito. Sci Rep 7:3476. https://doi.org/10.1038/s41598-017-03720-x

Jones CM, Liyanapathirana M, Agossa FR et al (2012a) Footprints of positive selection associated with a mutation (N1575Y) in the voltage-gated sodium channel of Anopheles gambiae. Proc Natl Acad Sci 109:6614–6619. https://doi.org/10.1073/pnas.1201475109

Jones CM, Sanou A, Guelbeogo WM et al (2012b) Aging partially restores the efficacy of malaria vector control in insecticide-resistant populations of Anopheles gambiae sl. from Burkina Faso. Malar J 11:24

Kambris Z, Blagborough AM, Pinto SB et al (2010) Wolbachia stimulates immune gene expression and inhibits plasmodium development in anopheles gambiae. PLoS Pathog 6. https://doi.org/10.1371/journal.ppat.1001143

Karunamoorthi K, Sabesan S (2013) Insecticide resistance in insect vectors of disease with special reference to mosquitoes: A potential threat to global public health. Health Scope 2:4–18. https://doi.org/10.17795/jhealthscope-9840

Keita K, Camara D, Barry Y et al (2017) Species identification and resistance status of Anopheles gambiae s.l. (Diptera: Culicidae) mosquitoes in Guinea. J Med Entomol 54:677–681. https://doi.org/10.1093/jme/tjw228

Keïta M, Traoré S, Sogoba N et al (2016) Susceptibilité d'Anopheles gambiae sensu lato aux insecticides communément utilisés dans la lutte antivectorielle au Mali. Bull Soc Pathol Exot 109:39–45. https://doi.org/10.1007/s13149-015-0461-2

Khater HF (2012) Ecosmart biorational insecticides: alternative insect control strategies. In: Insecticides-advances in integrated pest management. InTech, London

Knox TB, Juma EO, Ochomo EO et al (2014) An online tool for mapping insecticide resistance in major Anopheles vectors of human malaria parasites and review of resistance status for the Afrotropical region. Parasit Vectors 7:76

Koffi AA, Alou LPA, Adja MA et al (2012) Update on resistance status of Anopheles gambiae ss to conventional insecticides at a previous WHOPES field site," Yaokoffikro", 6 years after the political crisis in Cote d'Ivoire. Parasit Vectors 5:68

Konan KG, Koné AB, Konan YL et al (2011) Résistance d'Anopheles gambiae s.l. aux pyréthrinoïdes et au DDT à Tiassalékro, village de riziculture irriguée en zone sud forestière de Côte-d'Ivoire. Bull Soc Pathol Exot 104:303–306. https://doi.org/10.1007/s13149-011-0176-y

Kyrou K, Hammond AM, Galizi R et al (2018) OPEN A CRISPR – Cas9 gene drive targeting doublesex causes complete population suppression in caged Anopheles gambiae mosquitoes. Nat Biotechnol 36. https://doi.org/10.1038/nbt.4245

Lacey LA (2007) Bacillus thuringiensis serovariety israelensis and Bacillus sphaericus for mosquito control. J Am Mosq Control Assoc 23:133–163 (: 10.2987/8756-971X(2007)23[133:BTSIAB]2.0.CO;2)

Liebman KA, Pinto J, Valle J et al (2015) Novel mutations on the ace-1 gene of the malaria vector Anopheles albimanus provide evidence for balancing selection in an area of high insecticide resistance in Peru. Malar J 14:74. https://doi.org/10.1186/s12936-015-0599-1

Liu N (2015) Insecticide resistance in mosquitoes: Impact, mechanisms, and research directions. Annu Rev Entomol 60:537–559. https://doi.org/10.1146/annurev-ento-010814-020828

Majambere S, Lindsay SW, Green C et al (2007) Microbial larvicides for malaria control in The Gambia. Malar J 6:76. https://doi.org/10.1186/1475-2875-6-76

Mancini MV, Spaccapelo R, Damiani C et al (2016) Paratransgenesis to control malaria vectors: A semi-field pilot study. Parasit Vectors 9:1–9. https://doi.org/10.1186/s13071-016-1427-3

Mitraka E, Stathopoulos S, Siden-Kiamos I et al (2013) *Asaia* accelerates larval development of *Anopheles gambiae*. Pathog Glob Health 107:305–311. https://doi.org/10.1179/2047773213Y.0000000106

Mohammed BR, Abdulsalam YM, Deeni YY (2015) Insecticide resistance to Anopheles spp. mosquitoes (Diptera: Culicidae) in Nigeria: A review. Int J Mosq Res 2:56–63

MR4 (2014) Methods in Anopheles research, 4th édn. USA

Murugan K, Priyanka V, Dinesh D et al (2015) Predation by Asian bullfrog tadpoles, Hoplobatrachus tigerinus, against the dengue vector, Aedes aegypti, in an aquatic environment treated with mosquitocidal nanoparticles. Parasitol Res 114:3601–3610. https://doi.org/10.1007/s00436-015-4582-0

Namountougou M, Simard F, Baldet T et al (2012) Multiple insecticide resistance in Anopheles gambiae s.l. Populations from Burkina Faso, West Africa. PLoS One 7:e48412. https://doi.org/10.1371/journal.pone.0048412

Nartey R, Owusu-Dabo E, Kruppa T et al (2013) Use of Bacillus thuringiensis var israelensis as a viable option in an Integrated Malaria Vector Control Programme in the Kumasi Metropolis, Ghana. Parasit Vectors 6:116

Nerio LS, Olivero-Verbel J, Stashenko E (2010) Repellent activity of essential oils: A review. Bioresour Technol 101:372–378. https://doi.org/10.1016/j.biortech.2009.07.048

Niang EHA, Konaté L, Diallo M et al (2016) Patterns of insecticide resistance and knock down resistance (kdr) in malaria vectors An. arabiensis, An. coluzzii and An. gambiae from sympatric areas in Senegal. Parasit Vectors 9:71. https://doi.org/10.1186/s13071-016-1354-3

Nicoletti M, Maccioni O, Coccioletti T et al (2011) Neem Tree (Azadirachta indica A. Juss) as Source of Bioinsectides. In: Insecticides - advances in integrated pest management, Janeza Trdine 9, 51000 Rijeka, Croatia. Farzana Perveen, pp 411–428

Niyondiko G, Langevin F, Barutel L (2013) Projet Faso Soap. https://www.faso-soap.info/

Author's personal copy

Oduola OA, Idowu ET, Oyebola MK et al (2012) Evidence of carbamate resistance in urban populations of Anopheles gambiae s.s. mosquitoes resistant to DDT and deltamethrin insecticides in Lagos, South-Western Nigeria. Parasit Vectors 5:116. https://doi.org/10.1186/1756-3305-5-116

Okorie PN, Ademowo OG, Irving H et al (2015) Insecticide susceptibility of Anopheles coluzzii and Anopheles gambiae mosquitoes in Ibadan, Southwest Nigeria: Susceptibility to insecticide of Anopheles. Med Vet Entomol 29:44–50. https://doi.org/10.1111/mve.12089

OMS O mondiale de la santé (2014) Entomologie du paludisme et lutte antivectorielle, Organisation mondiale de la santé. Geneva, Switzerland

Opondo KO, Weetman D, Jawara M et al (2016) Does insecticide resistance contribute to heterogeneities in malaria transmission in The Gambia? Malar J 15:166. https://doi.org/10.1186/s12936-016-1203-z

Ossè RA, Aïkpon R, Gbédjissi GL et al (2013) A shift from indoor residual spraying (IRS) with bendiocarb to long-lasting insecticidal (mosquito) nets (LLINs) associated with changes in malaria transmission indicators in pyrethroid resistance areas in Benin. Parasit Vectors 6:73

Padonou GG, Sezonlin M, Ossé R et al (2012) Impact of three years of large scale Indoor Residual Spraying (IRS) and Insecticide Treated Nets (ITNs) interventions on insecticide resistance in Anopheles gambiae sl. Benin Parasit Vectors 5:72

Parthipan P, Sarankumar RK, Jaganathan A et al (2018) Biosurfactants produced by Bacillus subtilis A1 and Pseudomonas stutzeri NA3 reduce longevity and fecundity of Anopheles stephensi and show high toxicity against young instars. Environ Sci Pollut Res 25:10471–10481. https://doi.org/10.1007/s11356-017-0105-0

Perveen F (2011) Insecticides - advances in integrated pest management. InTech, Rijeka

Phuc H, Andreasen MH, Burton RS et al (2007) Late-acting dominant lethal genetic systems and mosquito control. BMC Biol 5:11. https://doi.org/10.1186/1741-7007-5-11

Platt N, Kwiatkowska RM, Irving H et al (2015) Target-site resistance mutations (kdr and RDL), but not metabolic resistance, negatively impact male mating competiveness in the malaria vector Anopheles gambiae. Heredity 115:243–252

Prato M, Khadjavi A, Mandili G et al (2012) Insecticides as strategic weapons for malaria vector control. In: Insecticides-Advances in Integrated Pest Management. InTech, London

Price DN, Berry MS (2006) Comparison of effects of octopamine and insecticidal essential oils on activity in the nerve cord, foregut, and dorsal unpaired median neurons of cockroaches. J Insect Physiol 52:309–319

Raharimalala FN, Boukraa S, Bawin T et al (2016) Molecular detection of six (endo-) symbiotic bacteria in Belgian mosquitoes: first step towards the selection of appropriate paratransgenesis candidates. Parasitol Res 115:1391–1399. https://doi.org/10.1007/s00436-015-4873-5

Ranson H, Abdallah H, Badolo A et al (2009) Insecticide resistance in Anopheles gambiae: data from the first year of a multi-country study highlight the extent of the problem. Malar J 8:299. https://doi.org/10.1186/1475-2875-8-299

Ranson H, Lissenden N (2016) Insecticide resistance in African Anopheles mosquitoes: A Worsening situation that needs urgent action to maintain malaria control. Trends Parasitol 32:187–196. https://doi.org/10.1016/j.pt.2015.11.010

Ranson H, N'Guessan R, Lines J et al (2011) Pyrethroid resistance in African anopheline mosquitoes: what are the implications for malaria control? Trends Parasitol 27:91–98. https://doi.org/10.1016/j.pt.2010.08.004

Riveron JM, Osae M, Egyir-Yawson A et al (2016) Multiple insecticide resistance in the major malaria vector Anopheles funestus in southern Ghana: implications for malaria control. Parasit Vectors 9:504. https://doi.org/10.1186/s13071-016-1787-8

Riveron JM, Yunta C, Ibrahim SS et al (2014) A single mutation in the GSTe2 gene allows tracking of metabolically based insecticide resistance in a major malaria vector. Genome Biol 15:R27

Roni M, Murugan K, Panneerselvam C et al (2015) Characterization and biotoxicity of Hypnea musciformis-synthesized silver nanoparticles as potential eco-friendly control tool against Aedes aegypti and Plutella xylostella. Ecotoxicol Environ Saf 121:31–38. https://doi.org/10.1016/j.ecoenv.2015.07.005

Sadia-Kacou CM, Alou LPA, Edi AV et al (2017) Presence of susceptible wild strains of Anopheles gambiae in a large industrial palm farm located in Aboisso, South-Eastern of Cote d'Ivoire. Malar J 16:157

Samb B, Konate L, Irving H et al (2016) Investigating molecular basis of lambda-cyhalothrin resistance in an Anopheles funestus population from Senegal. Parasit Vectors 9:449. https://doi.org/10.1186/s13071-016-1735-7

Seye F, Bawin T, Boukraa S et al (2014) Pathogenicity of Aspergillus clavatus produced in a fungal biofilm bioreactor toward Culex quinquefasciatus (Diptera: Culicidae). J Pestic Sci 39:127–132. https://doi.org/10.1584/jpestics.D14-006

Sharma A, Dhayal D, Singh OP et al (2013) Gut microbes influence fitness and malaria transmission potential of Asian malaria vector Anopheles stephensi. Acta Trop 128:41–47. https://doi.org/10.1016/j.actatropica.2013.06.008

Slatko BE, Luck AN, Dobson SL, Foster JM (2014) Wolbachia endosymbionts and human disease control. Mol Biochem Parasitol 195:88–95. https://doi.org/10.1016/j.molbiopara.2014.07.004

Solomon B, Gebre-Mariam T, Asres K (2012) Mosquito repellent actions of the essential oils of Cymbopogon citratus, Cymbopogon nardus and Eucalyptus citriodora : Evaluation and formulation studies. J Essent Oil Bear Plants 15:766–773. https://doi.org/10.1080/0972060X.2012.10644118

Soumaila H, Idrissa M, Akgobeto M et al (2017) Multiple mechanisms of resistance to pyrethroids in Anopheles gambiae s.l populations in Niger. Méd Mal Infect 47:415–423. https://doi.org/10.1016/j.medmal.2017.04.012

Sovi A, Djègbè I, Soumanou L et al (2014) Microdistribution of the resistance of malaria vectors to deltamethrin in the region of Plateau (southeastern Benin) in preparation for an assessment of the impact of resistance on the effectiveness of Long Lasting Insecticidal Nets (LLINs). BMC Infect Dis 14:103. https://doi.org/10.1186/1471-2334-14-103

Tchioffo MT, Boissière A, Abate L et al (2016) Dynamics of bacterial community composition in the malaria mosquito's epithelia. Front Microbiol 6:1–9. https://doi.org/10.3389/fmicb.2015.01500

Temu EA, Maxwell C, Munyekenye G et al (2012) Pyrethroid resistance in Anopheles gambiae, in Bomi County, Liberia, compromises malaria vector control. PLoS One 7:e44986. https://doi.org/10.1371/journal.pone.0044986

Tia E, Chouaibou M, Gbalégba CNG et al (2017) Distribution des espèces et de la fréquence du gène Kdr chez les populations d'Anopheles gambiae s.s. et d'Anopheles coluzzii dans cinq sites agricoles de la Côte d'Ivoire. Bull Soc Pathol Exot 110:130–134. https://doi.org/10.1007/s13149-017-0554-1

Toé KH, Jones CM, N'Fale S et al (2014) Increased pyrethroid resistance in malaria vectors and decreased bed net effectiveness, Burkina Faso. Emerg Infect Dis 20:1691–1695. https://doi.org/10.3201/eid2010.140619

Vontas J, Grigoraki L, Morgan J et al (2018) Rapid selection of a pyrethroid metabolic enzyme CYP9K1 by operational malaria control activities. Proc Natl Acad Sci 115:4619–4624. https://doi.org/10.1073/pnas.1719663115

Wangrawa D, Badolo A, Guelbéogo W et al (2015) Biological activities of four essential oils against Anopheles gambiae in Burkina Faso

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and their in vitro inhibition of acetylcholinesterase. Int J Biol Chem Sci 9:793–802. https://doi.org/10.4314/ijbcs.v9i2.19

Wangrawa DW, Badolo A, Guenne S, Sanon A (2016) Larvicidal and oviposition-deterrence activities of four local plant extracts from Burkina Faso against Anopheles gambiae S. l.(Diptera: Culicidae). 3:11–19

Wangrawa DW, Badolo A, Ilboudo Z et al (2018) Insecticidal activity of local plants essential oils against laboratory and field strains of Anopheles gambiae s. l. (Diptera: Culicidae) from Burkina Faso. J Econ Entomol 11:2844–2853. https://doi.org/10.1093/jee/toy276

WHO (2018) World malaria report 2018. World Health Organization, Geneva

WHO (2016) World malaria report 2016. World Health Organization, Geneva, Switzerland

WHO (2015a) Indoor residual spraying: an operational manual for indoor residual spraying (IRS) for malaria transmission control and elimination. World Health Organization, Geneva, Switzerland

WHO (2015) Global technical strategy for malaria, 2016–2030. World Health Organization. Geneva, Geneva

WHO (2012) Global plan for insecticide resistance management in malaria vectors. World Health Organization, Geneva

Wilke ABB, Beier JC, Benelli G (2018) Transgenic mosquitoes – Fact or fiction? Trends Parasitol 34:456–465. https://doi.org/10.1016/j.pt.2018.02.003

Wondji CS, Dabire RK, Tukur Z et al (2011) Identification and distribution of a GABA receptor mutation conferring dieldrin resistance in the malaria vector Anopheles funestus in Africa. Insect Biochem Mol Biol 41:484–491. https://doi.org/10.1016/j.ibmb.2011.03.012

Yadav KK, Bora A, Datta S et al (2015) Molecular characterization of midgut microbiota of Aedes albopictus and Aedes aegypti from Arunachal Pradesh, India. Parasit Vectors 8:1–8. https://doi.org/10.1186/s13071-015-1252-0

Yadouleton AW, Padonou G, Asidi A et al (2010) Insecticide resistance status in Anopheles gambiae in southern Benin. Malar J 9:83

Yahouédo GA, Cornelie S, Djègbè I et al (2016) Dynamics of pyrethroid resistance in malaria vectors in southern Benin following a large scale implementation of vector control interventions. Parasit Vectors 9:385. https://doi.org/10.1186/s13071-016-1661-8

Yang C, Feng X, Huang Z et al (2016) Diversity and frequency of kdr mutations within Anopheles sinensis populations from Guangxi, China. Malar J 15:411. https://doi.org/10.1186/s12936-016-1467-3

Yoshida S, Ioka D, Matsuoka H et al (2001) Bacteria expressing single-chain immunotoxin inhibit malaria parasite development in mosquitoes. Mol Biochem Parasitol 113:89–96

Zhang Y, Meng X, Yang Y et al (2016) Synergistic and compensatory effects of two point mutations conferring target-site resistance to fipronil in the insect GABA receptor RDL. Sci Rep 6:32335. https://doi.org/10.1038/srep32335

Zoh DD, Ahoua Alou LP, Toure M et al (2018) The current insecticide resistance status of Anopheles gambiae (s.l.) (Culicidae) in rural and urban areas of Bouaké, Côte d'Ivoire. Parasit Vectors 11:118. https://doi.org/10.1186/s13071-018-2702-2

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