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RESEARCH PAPER

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Susceptibility of *Culex quinquefasciatus* to insecticides in the industrial areas of Koumassi, Vridi, and Yopougon in Abidjan, Ivory Coast, during the rainy season

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ABSTRACT

Insecticide resistance in *Culex quinquefasciatus* is an important concern for urban vector control because it can reduce the effectiveness of chemical interventions and undermine public acceptance of insecticide-based mosquito control. This study assessed the susceptibility of *C. quinquefasciatus* populations collected during the 2025 rainy season from the industrial zones of Koumassi, Vridi (Port-Bouët), and Yopougon in Abidjan, Côte d'Ivoire. Larvae were collected from residential, non-chemical industry, chemical industry, and chemical and other materials industry sites, reared to adulthood, and 3–5-day-old females were tested using WHO susceptibility assays. Diagnostic, 5×, and 10× concentrations of pyrethroids were evaluated alongside 5% malathion, 0.1% bendiocarb, and 4% DDT, while 4% piperonyl butoxide (PBO) assays were used to investigate metabolic resistance. At diagnostic concentrations, resistance or suspected resistance was observed across the three industrial zones, whereas malathion produced 98–100% mortality at the Vridi residential site and the INC and ICAM sites in Yopougon. Mortality at 10× pyrethroid concentrations remained below 98% across the sites evaluated, indicating high resistance intensity. Malathion produced the shortest Kdt50/Kdt95 values, reaching 36.34/64.24 min in Yopougon. PBO did not consistently restore susceptibility, indicating that monooxygenases were not the sole resistance mechanism. These findings demonstrate substantial insecticide resistance and support continued susceptibility monitoring to guide effective vector-control strategies in Abidjan's industrial areas.

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INTRODUCTION

Like most cities in West Africa, Abidjan, the economic capital of Côte d'Ivoire, is experiencing rapid, uncontrolled urbanization combined with accelerated industrialization—all without a rigorous waste management policy—which has led to changes in the natural environment and significant environmental imbalances (Dongo *et al.*, 2013). This situation has created conditions conducive to the reproduction and survival of many disease-carrying insects, such as mosquitoes (Aouinty *et al.*, 2017; Zahouli *et al.*, 2017; Koumba *et al.*, 2018).

These insects are responsible for several diseases, including malaria, arboviral diseases, and filariasis.

In West Africa, Culex quinquefasciatus is the primary source of nuisance in urban areas. In Côte d'Ivoire, this mosquito accounted for more than 90% of the anthropophagous Culicidae captured in most municipalities of the city of Abidjan in 1991 (Subra, 1973). Methods for controlling these disease vectors are largely dominated by chemical control (OMS, 2019).

However, the resistance of disease-carrying insects in general—and Culex quinquefasciatus in particular—to chemical active ingredients with insecticidal properties remains a threat to the effectiveness of vector control methods.

The phenomenon of resistance in Culex quinquefasciatus, as described by several authors (Chandre *et al.*, 1997; Konan, 2002; Mouchet *et al.*, 1968; Subra, 1968), is of particular concern in urban areas, where it poses a threat to the implementation of malaria control strategies based on the use of long-lasting insecticide-treated bed nets (LLINs), when the insecticide used to treat the nets is effective against malaria vectors but ineffective against Culex quinquefasciatus due to its abundance. This also applies to indoor residual spraying of insecticides as a means of vector control targeting malaria vectors. Furthermore, the resistance of Culex quinquefasciatus to chemical insecticides could be influenced by activities carried out within industrial zones.

Given these facts, it is essential to understand the level of susceptibility of Culex quinquefasciatus to insecticides in any urban area where vector control activities are planned.

In this context, a study assessing the susceptibility of Culex quinquefasciatus was conducted at the industrial zone level in three municipalities of the city of Abidjan (Koumassi, Port-Bouet, and Yopougon), taking into account the activities and residential areas within them, in order to further refine the consideration of these criteria in the planning of vector control strategies at the local level.

MATERIALS AND METHODS

Study area

This study was conducted in the three main industrial zones of the city of Abidjan, located in the municipalities of Koumassi, Port-Bouët, and Yopougon, from June to July 2025 (rainy season) (Fig. 1). The city of Abidjan (5° 20′ 11″ North and 4° 01′ 36″ West) is located in southeastern Côte d'Ivoire, on the coast of the Gulf of Guinea (Mobio *et al.*, 2017). This city, which is experiencing rapid population growth, rapid urbanization, and significant industrialization, is bisected by the Ébrié Lagoon and covers an area of 422 km² (RGPH, 2021). The climate of Abidjan is subequatorial, hot, and humid, characterized by distinct rainy and dry seasons. The long rainy season generally extends from April to July, followed by a short dry season in August and a short rainy season from September to November, while the main dry season occurs from December to March. Precipitation is relatively abundant, averaging approximately 1,500 mm per year, and temperatures remain generally high throughout the year (Mobio *et al.*, 2017).

Mosquito larvae sampling

Mosquito larvae were sampled at four sites previously selected within each industrial zone. The sampling sites were selected based on specific criteria, including areas with high concentrations of residential housing located on the outskirts of or within the industrial zone; areas with high concentrations of industries using chemicals and other materials, particularly where such industries were most densely distributed within the industrial zone; and areas with high concentrations of industries that did not use chemicals. Sampling was conducted within a 200-m radius around each designated sampling point within the same industrial zone.

The survey involved systematically searching for all potential larval breeding sites (pools of water, containers, abandoned tires, stagnant water) available in each industrial zone. The survey was conducted within a 200-meter radius of each sampling point. After visually confirming the presence of immature stages in the larval habitat, they were sampled using the dipping method (Talipouo *et al.,* 2017). For small breeding sites (boxes, cans, etc.), larvae and nymphs were collected using a pipette. After collection, the samples were transferred to labeled jars—one jar per larval habitat—and transported to the insectarium at the National Institute of Public Health, where they were reared (at a temperature of 28 ± 5°C and relative humidity of 70–78%) until they reached adulthood. Female adults aged 2 to 5 days were isolated to undergo the susceptibility test.

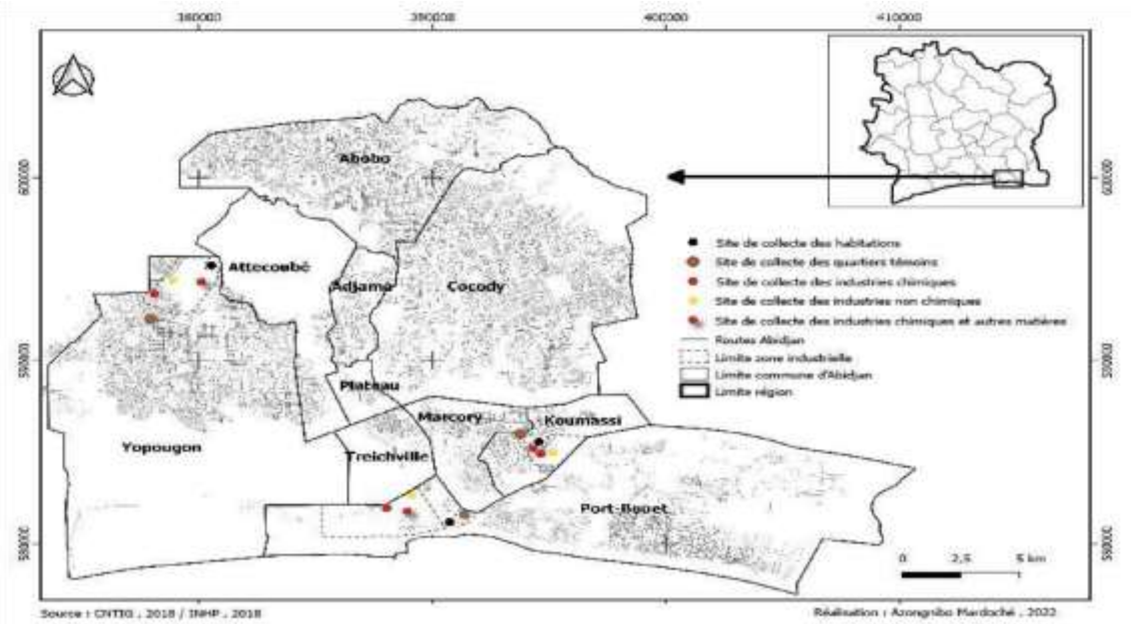

Fig. 1. Locations of the study sites

Insecticides test

Insecticide-impregnated papers were obtained through WHO/AFRO from its reference center (Vector Control Research Unit, Universiti Sains Malaysia, Penang, Malaysia). Six insecticides (on impregnated papers) belonging to four families were tested at the following concentrations:

Organochlorines: DDT 4%;
Organophosphates: malathion 5%;
Carbamates : bendiocarb 0.1% ;
Pyrethroids: permethrin 0.75%; 3.75%; 7.5%; deltamethrin 0.05%; 0.25%; 0.5%; and lambda-cyhalothrin 0.05%; 0.25%; 0.5%.

Biological insecticide susceptibility test

Susceptibility tests were conducted on fasted 3- to 5-day-old female Culex quinquefasciatus mosquitoes, following the WHO standard protocol for adults using WHO kits (OMS, 2023).

The tests were conducted in a room where the temperature was maintained at 25°C and relative humidity between 70–80%. For each test, ten tubes were used (two control tubes, four observation tubes, and four exposure tubes). In each tube, the females were introduced in batches of approximately 20–25 females. Each test was conducted in two stages : first, the batches of mosquitoes were placed under

Vol. 29, Issue: 1, p. 175-185, 2026

observation for one hour in tubes lined with non-impregnated paper (12 × 15 cm) ; in a second step, the females were exposed to the insecticide in tubes lined with impregnated paper (12 × 15 cm), while the control females were placed in tubes lined with non-impregnated paper. During the 60-minute exposure period, the knockdown (kd) effect—that is, the number of females that had fallen lifeless to the bottom of the OMS tubes—was observed at the following time points : 5, 10, 15, 20, 30, 40, 50, and 60 minutes. At the end of this period, the females were transferred to observation tubes. A cotton swab soaked in a 10% honey solution was then placed on each observation tube to feed the mosquitoes, thereby ruling out hunger as a cause of mortality. Mortality was then assessed 24 hours after exposure to the insecticide (WHO, 1998 ; OMS, 2017, OMS, 2023) The susceptible strain SEB was tested to verify the quality of the insecticidal papers used.

Synergistic bioassays

To evaluate the role of detoxifying enzymes in resistance to deltamethrin, permethrin, lambda-cyhalothrin (an insecticide used to treat mosquito nets), and DDT, tests with the synergist were conducted following pre-exposure to 4% PBO (piperonyl butoxide), an inhibitor that primarily targets monooxygenases (OMS, 2023). Each test was conducted in three stages with four batches consisting of 20 to 25 unfed female Aedes aegypti mosquitoes aged 3 to 5 days. The four groups were divided as follows: 1 group tested with the synergist alone, 1 group tested with the insecticide (0.05% deltamethrin or 4% DDT) alone, 1 group tested with the synergist followed by the insecticide, and 1 control group exposed to untreated paper. First, the groups of females were observed for one hour in tubes lined with untreated paper (12 × 15 cm). Next, two groups of 20 to 25 females each were placed in tubes lined with paper impregnated with the synergist for one hour. Finally, in a third step, the females tested with the synergist alone were transferred back to the observation tube, and the females in the other three groups were transferred to the exposure tubes. The transfer was carried out as follows: the group to be tested with the synergist and then the insecticide was transferred to the tube containing the insecticide; the group to be tested with the insecticide was transferred to a tube containing paper impregnated with insecticide; and the control group was transferred to a tube containing non-impregnated paper. After 1 hour of exposure, the three groups were transferred back to their respective observation tubes, which were filled with a 10% honey-water solution, and kept there for 24 hours before mortality was recorded. After the tests, the dead and live mosquitoes were placed in Eppendorf tubes on silica gel and stored at -20°C for the investigation of resistance mechanisms.

Interpretation of the test

The data were entered into a Microsoft Excel spreadsheet. The validity of the test was determined based on the mortality observed in the control group:

1. Mortality <5%: The test was considered valid.
2. Mortality >5% but <20%: Mortality was corrected using Abbott's formula.
3. Mortality ≥20%: The results were rejected, and the test was repeated.

Resistance status was determined according to the WHO protocol based on mortality recorded 24 hours after exposure:

1. Mortality ≥98%: Susceptible.
2. Mortality 90–97%: Suspected resistance.
3. Mortality <90%: Resistant.

Resistance intensity was assessed according to the WHO protocol using 5× and 10× diagnostic concentrations:

1. Mortality of 98–100% at the 5× concentration: Indicates low resistance intensity; testing at the 10× concentration is not necessary.
2. Mortality <98% at the 5× concentration: Indicates moderate resistance intensity, and further testing at the 10× concentration is recommended.
3. Mortality of 98–100% at the 10× concentration: Confirms moderate resistance intensity.
4. Mortality <98% at the 10× concentration: Indicates high resistance intensity.

The synergistic effect of piperonyl butoxide (PBO) was interpreted according to the WHO protocol:

1. When the mean mortality in samples exposed to the insecticide alone was ≥90%, the effect of PBO could not be reliably assessed.
2. When the mean mortality in samples exposed to the insecticide alone was <90%, the effect of PBO was interpreted based on the mortality observed following exposure to PBO and the insecticide.
3. Complete restoration of susceptibility, defined as a mean mortality of ≥98% following exposure to PBO and subsequently to the insecticide, indicates that a resistance mechanism involving monooxygenases is fully responsible for the expression of the resistant phenotype in the tested population.

Data analysis

A p-value of 0.05 or less was considered statistically significant. BioStat software, version 5.0, was used to calculate the knockdown times (Kdt50) and (Kdt95).

RESULTS

During this study, mortality rates using the susceptible laboratory strain "SLAB" ranged from 98% to 100% with deltamethrin, permethrin, lambda-cyhalothrin, malathion, bendiocarb, and DDT. These rates attest to the quality of the insecticide-impregnated papers used. The mortality rates of <5% observed in control mosquitoes from the industrial sites of Koumassi, Port-Bouët, and Yopougon confirm the validity of the tests conducted. Furthermore, no mortality rates were corrected using the Abbott formula.

Sensitivity of *Culex quinquefasciatus* to diagnostic doses of insecticides at industrial site Locations

Knockdown times and mortality rates for *Culex quinquefasciatus* at the industrial sites in Koumassi, Vridi, and Yopougon are presented in Tables 1, 2, and 3. Female *Culex quinquefasciatus* collected from the residential site in Vridi (Port-Bouët) and from the non-chemical industries (INC) and chemical and other materials industries (ICAM) sites in Yopougon had mortality rates ranging from 98–100% with malathion, suggesting their sensitivity to this insecticide. Mortality rates observed at the other sites ranged from 0% to 97% for all insecticides tested. Resistance or suspected resistance to these insecticides was observed in all three industrial zones (Tables 1, 2, and 3).

Table 1. Mortality of *Culex quinquefasciatus* at diagnostic doses of insecticides in the Koumassi industrial zone during the 2025 rainy season

Insecticides	Collection sites	Mosquitoes tested (N)	Dead mosquitoes (n)	Mortality (%)	Kdt50 (Min) [95% CI]	Kdt95 (Min)[95% CI]	Status
Deltamethrin 0,05%	Hb	99	0	0	—	—	R
	INC	74	3	4,05	—	—	R
	IC	78	6	7,69	—	—	R
	ICAM	78	1	1,28	—	—	R
Permethrin 0,75%	Hb	95	0	0	—	—	R
	INC	82	2	2,44	—	—	R
	IC	78	1	1,28	—	—	R
	ICAM	77	0	0	—	—	R
Lambdacyalothrin 0,05%	Hb	88	0	0	—	—	R
	INC	85	2	2,35	—	—	R
	IC	81	0	0	—	—	R
	ICAM	79	0	0	—	—	R
Malathion 5%	Hb	97	81	83,51	65,63 (61,56-73,29)	98,42 (84,49-131,58)	R
	INC	77	71	92,21	65,83 (58,66-78,31)	166,61 (125,34-267,44)	SR
	IC	78	76	97,44	48,97 (46,88-51,34)	76,05 (69,46-86,80)	SR
	ICAM	77	70	90,91	51,81 (48,85-55,65)	94,77 (82,32-117,37)	SR
Bendiocarb 0,1%	Hb	90	29	32,22	69,80 (63,77-82,68)	115,80 (93,78-177,61)	R
	INC	78	9	11,54	126,36 (85,52-977,51)	310,75 (146,92-17534,46)	R
	IC	74	45	60,81	64,01 (59,02-73,17)	112,15 (91,92-162,38)	R
	ICAM	77	13	16,88	112,53 (82,90-283,59)	293,35 (157,34-2059,44)	R
DDT 4%	Hb	88	0	0	—	—	R
	INC	78	2	2,56	—	—	R
	IC	81	1	1,23	—	—	R
	ICAM	77	0	0	—	—	R

IZ: Industrial Zone; Hb: Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; %M: Percentage of Deaths; Kdt50: knock-down times for 50% of mosquitoes, expressed in minutes; Kdt95: knock-down times for 95% of mosquitoes, expressed in minutes; CI: Confidence Interval; R: Resistant; S: Susceptible; SR: Suspected Resistance

Table 2. Mortality of *Culex quinquefasciatus* at diagnostic doses of insecticides in the Vridi industrial zone (Port-Bouet) during the 2025 rainy season

Insecticides	Collection sites	Mosquitoes tested (N)	Dead mosquitoes (n)	Mortality (%)	Kdt50 (Min) [95% CI]	Kdt95 (Min)[95% CI]	Status
Deltamethrin 0,05%	Hb	76	3	3,95	---	---	R
	INC	78	5	6,41	---	---	R
	IC	77	1	1,30	---	---	R
	ICAM	82	1	1,22	155,48 (94,35-3128,82)	449,79 (176,38-142171,61)	R
Permethrin 0,75%	Hb	78	2	2,56	---	---	R
	INC	77	3	3,90	---	---	R
	IC	78	2	2,56	---	---	R
	ICAM	78	2	2,56	---	---	R
Lambdacyalothrin 0,05%	Hb	77	4	5,19	---	---	R
	INC	75	7	9,33	---	---	R
	IC	76	1	1,32	---	---	R
	ICAM	79	0	0	---	---	R
Malathion 5%	Hb	79	79	100	45,14 (43,08-47,34)	73,46 (67,15-83,30)	S
	INC	77	71	92,21	44,93 (41,73-48,87)	108,81 (91,73-138,10)	SR
	IC	74	70	94,59	75,33 (66,03-99,05)	144,68 (106,95-283,70)	SR
	ICAM	75	68	90,67	66,59 (54,33-135,37)	145,47 (91,11-1143,73)	SR
Bendiocarb 0,1%	Hb	75	19	25,33	79,61 (68,61-127,33)	129,80 (94,89-368,04)	R
	INC	81	14	17,28	78,88 (68,33-145,08)	117,35 (87,60-431,08)	R
	IC	75	13	17,33	96,72 (75,16-302,39)	184,88 (112,11-1924)	R
	ICAM	78	8	10,26	70,94 (64,86-109,49)	91,69 (75,93-243,11)	R
DDT 4%	Hb	78	0	0	---	---	R
	INC	78	0	0	---	---	R
	IC	79	0	0	---	---	R
	ICAM	81	2	2,47	---	---	R

IZ: Industrial Zone; Hb : Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; %M: Percentage of Deaths; Kdt50: knock-down times for 50% of mosquitoes, expressed in minutes; Kdt95: knock-down times for 95% of mosquitoes, expressed in minutes; CI: Confidence Interval; R: Resistant; S: Susceptible; SR: Suspected Resistance

Table 3. Mortality of *Culex quinquefasciatus* at diagnostic doses of insecticides in the Yopougon industrial zone during the 2025 rainy season

Insecticides	Collection sites	Mosquitoes tested (N)	Dead mosquitoes (n)	Mortality (%)	Kdt50 (Min) [95% CI]	Kdt95 (Min)[95% CI]	Status
Deltamethrin 0,05%	Hb	82	9	10,98	---	---	R
	INC	79	5	6,33	---	---	R
	IC	78	1	1,28	---		R
	ICAM	94	10	10,64	---	---	R
Permethrin 0,75%	Hb	81	5	6,17	---	---	R
	INC	81	2	2,47	---	---	R
	IC	74	3	4,05	---	---	R
	ICAM	95	4	4,21	---	---	R
Lambdacyalothrin 0,05%	Hb	80	4	5	---	---	R
	INC	80	3	3,75	---	---	R
	IC	74	1	1,35	---	---	R
	ICAM	93	6	6,45	---	---	R
Malathion 5%	Hb	78	73	93,59	64,24 (59,52-72,91)	108,19 (89,80-153,09)	SR
	INC	78	78	100	36,34 (32,05-40,83)	64,24 (54,37-86,77)	S
	IC	81	74	91,36	92,86 (75,32-145,48)	236,91 (149,63-664,26)	SR
	ICAM	94	94	100	55,35 (52,61-59,05)	92,93 (81,98-112,57)	S
Bendiocarb 0,1%	Hb	75	26	34,67	78,56 (68,02-110,98)	143,04 (104,07-321,29)	R
	INC	77	27	35,06	99,33 (77,67-191,94)	237,50 (141,65-1002,55)	R
	IC	74	10	13,51	98,19 (74,35-1487,80)	173,63 (102,34-36158,84)	R
	ICAM	79	26	32,91	77,78 (67,59-104,46)	152,91 (111,21-311,51)	R
DDT 4%	Hb	77	3	3,90	---	---	R
	INC	79	1	1,27	---	---	R
	IC	79	0	0	---	---	R
	ICAM	81	0	0	---	---	R

IZ: Industrial Zone; Hb: Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; %M: Percentage of Deaths; Kdt50: knock-down times for 50% of mosquitoes, expressed in minutes; Kdt95: knock-down times for 95% of mosquitoes, expressed in minutes; CI: Confidence Interval; R: Resistant; S: Susceptible; SR: Suspected Resistance

The mean knockdown times (Kdt50 and Kdt95) could not be estimated for DDT and pyrethroids, except for deltamethrin at the ICAM site in Vridi. The lowest Kdt50 and Kdt95 values were 48.97 and 76.05 minutes, respectively, in Koumassi ; 44.93 and 73.46 minutes in Vridi ; and 36.34 and 64.24 minutes in

Yopougon with malathion. Meanwhile, the highest Kdt50 and Kdt95 values were 126.36 and 310.75 minutes, respectively, in Koumassi ; 99.33 and 237.50 minutes in Yopougon with bendiocarb; and 155.48 and 449.79 minutes in Vridi with deltamethrin. Malathion had the fastest mode of action compared to the other compounds against *Culex quinquefasciatus* in industrial areas.

Sensitivity of *Culex quinquefasciatus* to 5x and 10x the diagnostic doses of insecticides at sites in industrial areas

Table 4. Mortality of *Culex quinquefasciatus* collected in Koumassi, Port-Bouët, and Yopougon during the rainy season after exposure to 5 times the diagnostic doses of insecticides over a 24-hour observation period in 2025

Locations	Collection sites	Deltamethrin 0,25% (%M)	Permethrin 3,75% (%M)	Lambdacyalothrin 0,25% (%M)
IZ Koumassi	Hb	9,46	13,27	11,27
	INC	6,67	30	15,58
	IC	18,92	11,36	8
	ICAM	1,25	25	25
IZ Vridi	Hb	30,95	41,18	31,11
	INC	12,33	39,47	21,92
	IC	22,54	25,71	40,54
	ICAM	3,75	7,5	6,33
IZ Yopougon	Hb	50,65	67,9	62,96
	INC	42,67	53,75	39,74
	IC	7,69	15,58	15,58
	ICAM	10	53,85	45,45

IZ: Industrial Zone; Hb: Habitation; INC : Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; %M: Percentage of Deaths

Table 5. Mortality of *Culex quinquefasciatus* following exposure to 10 times the diagnostic doses of insecticides after 24 hours of observation in Koumassi, Port-Bouët, and Yopougon during the 2025 rainy season

Locations	Collection sites	Deltamethrin 0,5% (%M)	Permethrin 7,5% (%M)	Lambdacyalothrin 0,5% (%M)
IZ Koumassi	Hb	17,95	48,96	23,17
	INC	27,71	73,42	23,68
	IC	47,37	56,18	43,04
	ICAM	21,79	50,65	30,86
IZ Vridi	Hb	49,35	65,82	47,56
	INC	40,51	64,94	44,59
	IC	48,61	61,64	45,95
	ICAM	16,88	28,75	15
IZ Yopougon	Hb	74,65	87,67	76,71
	INC	53,95	94,74	51,95
	IC	25,68	62,03	25,33
	ICAM	14,1	56,41	46,25

IZ: Industrial Zone; Hb: Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; %M: Percentage of Deaths

Resistance (mortality<98%) in *Culex quinquefasciatus* populations at most of our study sites to 5x the diagnostic dose of pyrethroids (permethrin 3.75%, deltamethrin 0.25%, lambdacyhalothrin 0.25%) indicated moderate to high resistance levels, which will be confirmed by further testing at 10x the diagnostic doses. In contrast, in the Yopougon industrial zone, *Culex quinquefasciatus* populations were susceptible to 3.75% permethrin, 0.25% deltamethrin, and 0.25% lambda-cyhalothrin at the residential site, with mortality after 24 hours of observation greater than or equal to 98%, indicating a low level of resistance (Table 4).

Populations of *Culex quinquefasciatus* showed resistance or suspected resistance to 7.5% permethrin, 0.5% deltamethrin, and 0.5% lambda-cyhalothrin, with mortality rates after 24 hours of observation ranging from 46 to 95%, indicating a high level of resistance. In contrast, at the residential site in Vridi (Port-Bouet), *Culex quinquefasciatus* were susceptible to 0.5% lambda-cyhalothrin, with a mortality rate of 98.85%, suggesting a moderate level of resistance (Table 5).

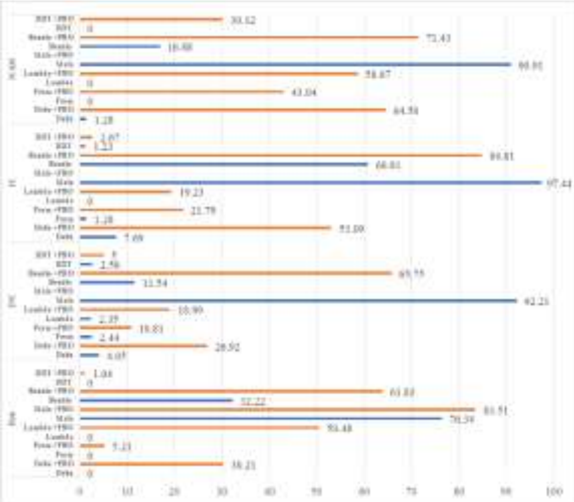

Fig. 2. Mortality of *Culex quinquefasciatus* following pre-exposure to 4% PBO and diagnostic doses of insecticides after 24 hours of observation in Koumassi during the 2025 rainy season

Hb: Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; Delta: Deltamethrin; Perm: Permethrin; Lambda: Lambda-cyhalothrin; Bendio: Bendiocarb

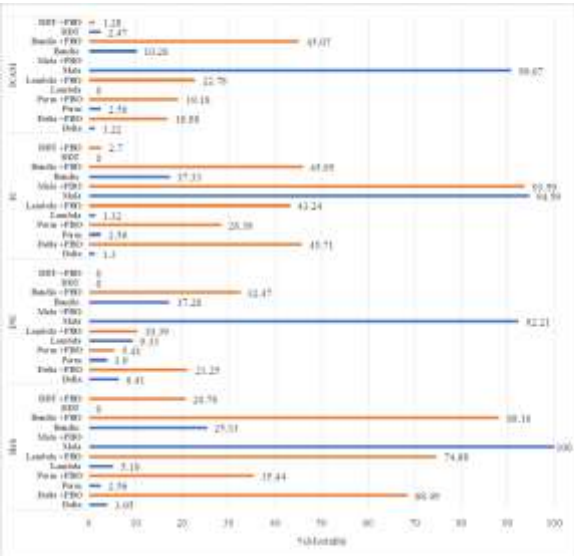

Fig. 3. Mortality of *Culex quinquefasciatus* following pre-exposure to 4% PBO and diagnostic doses of insecticides after 24 hours of observation in Vridi during the 2025 rainy season

Hb: Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; Delta: Deltamethrin; Perm: Permethrin; Lambda: Lambda-cyhalothrin; Bendio: Bendiocarb

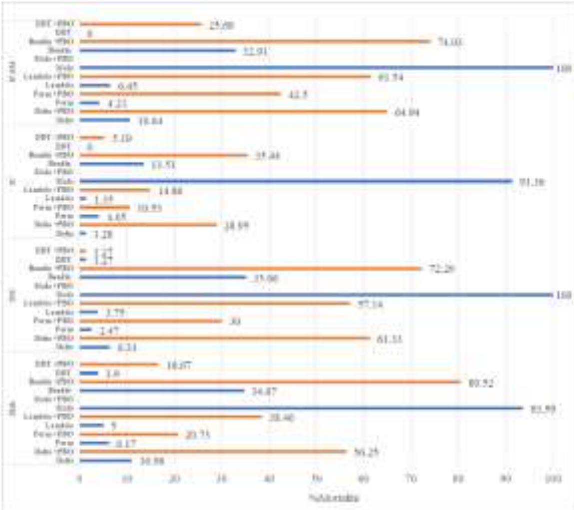

Fig. 4. Mortality of *Culex quinquefasciatus* following pre-exposure to 4% PBO and diagnostic doses of insecticides after 24 hours of observation in Yopougon during the 2025 rainy season

Hb: Habitation; INC: Non-Chemical Industries; IC: Chemical Industries; ICAM: Chemical Industries and Other Materials; Delta: Deltamethrin; Perm: Permethrin; Lambda: Lambda-cyhalothrin; Bendio: Bendiocarb

Overall sensitivity was not restored in all *Culex quinquefasciatus* populations that had shown resistance to pyrethroids (permethrin 0.75%, deltamethrin 0.05%, and lambda-cyhalothrin 0.05%), organochlorines (DDT 4%), and carbamates (bendiocarb 0.1%), suggesting that metabolic resistance involving monooxygenases was not the sole mechanism underlying the resistance. However, at some study sites, pre-exposure to PBO restored susceptibility to bendiocarb, suggesting that a resistance mechanism involving monooxygenases is fully responsible for the expression of the resistant phenotype in the tested population (Fig. 2, 3, and 4).

DISCUSSION

Wild populations of *Culex quinquefasciatus* derived from larvae collected during the dry and rainy seasons at the various study sites were found to be resistant to 4% DDT, permethrin (0.75%, 3.75%, 7.5%), deltamethrin (0.05%, 0.25%, 0.5%), lambda-cyhalothrin (0.05%, 0.25%, 0.5%), bendiocarb 0.1%, and malathion 5% after 1 hour of contact with insecticide-impregnated paper and 24 hours of observation. The resistance of *Culex quinquefasciatus* populations to these insecticides is attributed to the Kdr gene, which causes a structural change in the sodium channel at the site of action of pyrethroids and DDT—the site where these insecticides act—as a resistance mechanism. Acetylcholinesterase (Ace.1R), a mutation in which affects the enzyme's structure, making the catalytic site less accessible to malathion and bendiocarb, thereby conferring cross-resistance to organophosphates and carbamates.

This resistance in *Culex quinquefasciatus* is not surprising, as this mosquito has been resistant to several insecticides in various African countries (Fofana *et al.,* 2012; Yadouléton *et al.,* 2015). It could also be explained by their lifestyle, specifically the larvae's exposure to industrial pollutants, which can trigger a wide range of responses in their biology and their sensitivity to insecticides. This resistance could therefore also be linked to the widespread use of pyrethroid-based aerosol sprays and fumigant coils in homes (Akogbéto and Yacoubou, 1999). These results are similar to those observed by Chandre and Rivière in Bobo (1994).

Populations of *Culex quinquefasciatus* in the industrial areas of Koumassi, Port-Bouët, and Yopougon exhibited a high level of resistance to the pyrethroids tested. These resistance levels are comparable to those previously observed in Côte d'Ivoire (Chandre, 1998).

This resistance poses a twofold problem. On the one hand, personal protection methods (aerosol sprays, coil incense, etc.) become ineffective ; on the other hand, urban residents' acceptance of the promotion of insecticide-treated bed nets to combat malaria is hindered by their ineffectiveness against the primary pest mosquito: *Culex quinquefasciatus* (Baldet, 1998). Furthermore, this resistance in *Culex quinquefasciatus*, combined with the already widespread resistance among malaria vectors, could affect public acceptance of MILDAs, given that promotional campaigns for these products often highlight their lethal effect on mosquitoes. Therefore, malaria control programs would benefit from incorporating into their monitoring programs a simultaneous assessment of the resistance of malaria vectors and *Culex quinquefasciatus* to insecticides used in public health. The complete restoration of *Culex quinquefasciatus*'s susceptibility to malathion, with mortality rates of ≥ 98% at residential sites in Vridi (Port-Bouët), non-chemical industries (INC), and chemical and other materials industries (ICAM) suggests that a resistance mechanism involving monooxygenases is fully responsible for the expression of the resistant phenotype in these tested populations.

Mortality rates below 98% following pre-exposure to PBO and then to insecticides (Koumassi, Port-Bouët, and Yopougon) showed that full susceptibility was not restored in all *Culex quinquefasciatus* populations that had exhibited resistance to pyrethroids, malathion, bendiocarb, and DDT at the study sites. This suggests that monooxygenases and other enzymes are involved in the expression of the resistant phenotype in the tested populations.

CONCLUSION

The resistance of mosquito populations to insecticides used in public health remains a reality that undermines the use of insecticide-treated bed nets in urban mosquito control. Wild populations of *Culex quinquefasciatus* were resistant to malathion but exhibited high mortality rates (50–97%) when exposed to other insecticides tested. Malathion could be used for indoor residual spraying (IRS) as an alternative to address the resistance developed by *Culex quinquefasciatus* to pyrethroids in the industrial areas of Koumassi, Vridi (Port-Bouët), and

Yopougon in the city of Abidjan. Therefore, it is necessary to establish a system for monitoring and evaluating the sensitivity of different mosquito populations to insecticides.

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