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Comparative study of the effect of solvents on the efficacy of neonicotinoid insecticides against malaria vector populations across Africa

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Abstract

Background: New insecticides with novel modes of action such as neonicotinoids have recently been recommended for public health use by WHO. Resistance monitoring of such novel insecticides requires a robust protocol to monitor the development of resistance in natural populations. In this study, we comparatively used three different solvents to assess the susceptibility of malaria vectors to neonicotinoids across Africa.

Methods: Mosquitoes were collected from May to July 2021 from three agricultural settings in Cameroon (Njombe-Penja, Nkolondom, and Mangoum), the Democratic Republic of Congo (Ndjili-Brasserie), Ghana (Atatam), and Uganda (Mayuge). Using the CDC bottle test, we compared the effect of three different solvents (ethanol, acetone, acetone+MERO) on the efficacy of neonicotinoids against *Anopheles gambiae* s.l. In addition, TaqMan assays were used to genotype key pyrethroid-resistant markers in *An. gambiae* and to evaluate potential cross-resistance between pyrethroids and clothianidin.

Results: Lower mortalities were observed for all populations when using absolute ethanol or acetone alone as solvent (11.4- 51.9% mortality for Nkolondom, 31.7-48.2% for Mangoum, 34.6- 56.1% for Mayuge, 39.4- 45.6% for Atatam, 83.7- 89.3% for Congo and 71.05- 95.9% for Njombe pendja) compared to acetone + MERO for which 100% mortality was observed for all the populations. Synergist assays (PBO, DEM and DEF) revealed a significant increase of mortality suggesting that metabolic resistance mechanisms are contributing to the reduced susceptibility. A negative association was observed between the L1014F-*kdr* mutation and clothianidin resistance with a greater frequency of homozygote resistant mosquitoes among the dead than among survivors (OR=0.5; P=0.02). However, the I114T-GSTe2 was in contrast significantly associated with a greater ability to survive clothianidin with a higher frequency of homozygote resistant among survivors than other genotypes (OR=2.10; P=0.013).

Conclusions: This study revealed a contrasted susceptibility pattern depending on the solvents with ethanol/acetone resulting in lower mortality, thus possibly overestimating resistance, whereas the addition of MERO consistently increased the efficacy of neonicotinoids in terms of percentage mortalities and time to final mortality. The addition of MERO could however prevent the early detection of resistance development. We therefore recommend monitoring susceptibility using both acetone alone and acetone+MERO (8-10µg/ml for clothianidin) to capture the accurate resistance profile of the mosquito populations.

Keywords: Malaria, *Anopheles gambiae*, vector control, neonicotinoids, cross-resistance

1. Introduction

Malaria prevention relies extensively on mosquito control using pyrethroid-based interventions including Indoor Residual Spraying (IRS) and Long-Lasting Insecticidal Nets (1, 2). The scale-up of these tools has significantly contributed to the important reduction of malaria burden in the past decade (1, 3). However, increasing resistance to pyrethroids in malaria vector species is a serious challenge to these vector control interventions given the heavy reliance on pyrethroid only (4). Most African *An. gambiae* and *An. funestus* populations are resistant to pyrethroid insecticides and show varying levels of resistance to other insecticides used for vector control (carbamates, organophosphates and organochlorines). Due to the threat posed by insecticide resistance, there has been an urgent call for alternative insecticides to supplement malaria vector control (5). Novel insecticides are gradually being introduced by manufacturers and recommended by WHO for vector control (6). Among these, the neonicotinoids (e.g clothianidin) and Pyrole (e.g Chlorfenapyr) are the new mode of action insecticide classes for public health, recently recommended by WHO for LLINs and IRS (7).

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Clothianidin is a neonicotinoid insecticide that is chemically like nicotine. It acts on the central nervous system of insects as an agonist of acetylcholine and stimulates nicotine acetylcholine receptors (nAChR) (8) activating post-synaptic acetylcholine receptors but does not inhibit acetyl cholinesterase (ACh). High levels overstimulate and block the receptors, (9) causing paralysis and death (8). Clothianidin is the active ingredient in SumiShield (developed by Sumitomo Chemical Company, Japan) and Fludora® Fusion (Bayer CropScience, Monheim, Germany) along with deltamethrin, an IRS formulation which was recently added to the WHO prequalification list of recommended insecticides (https://www.who.int/pq-vector-control/ prequalifed-lists/en/).

As new insecticides are developed, it is essential to monitor the development of resistance to prolong their efficacy as much as possible and avoid the level of widespread resistance now seen with pyrethroids (3). Such resistance monitoring requires establishing diagnostic concentrations to determine baseline susceptibility of malaria vectors and to enable surveillance of insecticide resistance once the insecticides are in use.

Currently, WHO protocol to test the susceptibility to neonicotinoids in mosquitoes is not well established thus, making resistance monitoring to this insecticide class very challenging. Clothianidin (Neonicotinoid; IRAC MoA class 4A) for example, tends to crystallize if used in straight acetone/ethanol (solvents commonly used in bioassays) and the uptake of active ingredient between the insect's body and the crystal is very low (10-12). This has made the design of standard protocols more arduous compared to other insecticide classes. In addition, because this active ingredient acts slowly, resistance profiles can be detected after bioassays only if exposed populations are rigorously monitored during a long holding period, which can last seven days or more. Despite these difficulties, the susceptibility of wild Anopheles populations from several African countries has been evaluated using 150µg/ml of clothianidin dissolved in either absolute ethanol or acetone (10-13). Recently, Bayer CropScience Ltd introduced an 81% Rapeseed oil

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methyl ester (1000ppm MERO®) which, added to acetone, prevents the crystallization then keeps the clothianidin for a longer period in a solved state and allows therefore the feasibility of the bottle assay. A study conducted in ivory coast, established 50µg/ml as diagnostic dose of clothianidin (14). However, this study did not evaluate the lower doses to see if 50µg/ml cannot mask the detection of resistance highlighting the need of standardizing the protocol for testing of neonicotinoids. In this study, we used three different solvents to comparatively evaluate the efficacy of neonicotinoids on malaria vectors from many African countries and established the diagnostic dose of clothiandin using acetone and MERO. Furthermore, we evaluated a potential cross-resistance between pyrethroids and clothianidin.

2. Materials and Methods

Study sites

Mosquitoes were collected from 4 regions across the continent. Mosquitoes were collected in three agricultural settings in Cameroon (Mangoum, Nkolondom, and Njombe-Penja) from May to July 2021. The climate is made up of two wet and two dry seasons typical of tropical climate around the equator. In the Democratic Republic of Congo (DRC) mosquitoes were collected at Ndjili Brasserie, a suburb of Kinshasa (4°19′39″S, 15°18′48″E), in June 2021. In Uganda, mosquitoes were collected in the Eastern region (May 2021), Mayµge (0°23′10.8″N, 33°37′16.5″E), and in Ghana collections were done in Atatam (5°56′ N, 1°37′ W) in the Adansi Asokwa District of the Ashanti Region in July 2021. In Cameroon, immature stages were collected from the breeding site using the dipping method whereas in other countries indoor resting blood fed females were collected using electric aspirators. Emerging adults (2-5days old) from collected larvae or F_1 progeny (2-5days old) from indoor collected females were used for the bioassays.

Molecular Identification

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Genomic DNA was extracted from a subset of mosquitoes from each of the collection sites using the Livak method [25], then the members of the *An. gambiae* complex was identified by PCR [26, 27].

Determination of susceptibility to neonicotinoids and establishment of the diagnostic dose of clothianidin using acetone + MERO **as a solvent**

Clothianidin, imidacloprid and acetamiprid used were technical materials from Sigma (PESTANAL®, analytical standard, Sigma-Aldrich, Dorset, United Kingdom). These chemicals were mixed in three different solvents (acetone, absolute ethanol, or acetone with MERO). For acetone and ethanol alone, the dose of 150µg/ml for clothianidin, 200 µg/ml for imidacloprid and 75µg/ml for acetamiprid were used as previously described (11).

For acetone dissolved in MERO, a stock solution of an acetone/MERO® mixture was made by pipetting 0.11ml (110µl) MERO® to 100ml of acetone (~1000ppm). 900µg straight clothianidin was weighed and mixed with 10ml of this stock solution of MERO plus acetone. After complete dissolution of the active ingredient, 10ml acetone/MERO® solution containing 900µg clothianidin was prepared. One (1) ml of this solution was applied to each test bottle to achieve a concentration of 90µg clothianidin /250ml bottle. This dose of insecticide was used to characterise the susceptibility of different mosquito populations. In addition, ranges of insecticide concentrations were tested (0.25, 0.50, 1, 2, 4, 40 and 90 µg/ml) using the susceptible lab strain Kisumu to evaluate the diagnostic dose of clothianidin when diluted in acetone and MERO. Approximately 24h after coating bottles with insecticide, 25 female Kisumu (3–5 days old) were exposed to the insecticides (ethanol/acetone or acetone +MERO without insecticide for the control group) for 1h and the knocked down mosquitoes were recorded at the end of the 60min (Kd-60) exposure period. After recording the Kd-60 mosquitoes were gently aspirated from the bottle into clean paper cups and provided with 10% sugar

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solution soaked in cotton wool during the recovery period and the final mortality was recorded 24h post-exposure.

Synergist assay with piperonyl butoxide (PBO), di-ethyl Maleate (DEM) and s,s,s–tri-butylphosphorotrithioate (DEF)

To identify the possible enzyme systems involved in reduced susceptibility to neonicotinoids, synergist bioassays were conducted for clothianidin in Nkolondom population using the emerging adult from larval collection. Two- to four-day-old F_0/F_1 females were first exposed to the synergist (4% PBO, 8% DEM or 0.25% DEF) for 1 h, followed by exposure to 150µg/ml clothianidin (dissolved in acetone) for 1 h. Mortality was recorded 24h after exposure and the differences in mortalities between synergized and non-synergized experiments were compared using a Chi-square test.

Potential cross-resistance between neonicotinoids and pyrethroids

To assess the potential cross-resistance between new neonicotinoids and pyrethroids, we crossed the pyrethroid highly resistant field strain from Nkolondom (where the 1014F-Kdr is fixed) with the fully susceptible laboratory strain Kisumu (with no 1014F-Kdr). This hybrid strain was exposed to clothianidin 150ug/ml (dissolved in acetone only) to select the dead and alive mosquitoes. These mosquitoes were genotyped for the L1014F target-site knockdown resistance (Kdr_w) and the 114T-GSTe2 metabolic resistance marker (all associated with DDT/pyrethroid resistance in *An. gambiae*) using Taqman methods as previously described (15, 16). PCR reactions (10 µl) contained 1 µl of genomic DNA, 5µl of SensiMix DNA kit (catalog: SM2-717104), 0.125µl of each probe and 3.875 µl of sigma water. Samples were run on a Mx3000P™ Multiplex quantitative PCR system with temperature cycling conditions of 10 minutes at 95°C followed by 40 cycles of 95°C for 10 seconds and 60°C for 45 seconds.

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Odds ratio and Fisher exact test were used to establish the statistical significance of any association between this DDT/pyrethroid resistance marker and the ability to survive clothianidin exposure.

3. Results

Molecular identification of mosquitoes tested

PCR assays revealed that all the mosquitoes tested from Mangoum (44/44), Nkolondom (50/50), and Congo (60/60) were *An. gambiae*. Those collected in Njombe (Cameroon) were mainly *An coluzzii* (58/60). The *An. gambiae* sl population from Uganda were a mix of 82% *An. gambiae* and 17% *An. arabiensis* whereas those from Atatam (Ghana) were 60% (39/65) *An. gambiae* and 40% (39/65) *An. coluzzii.*

Susceptibility profile to clothianidin

The Kisumu lab strain was susceptible to clothianidin whatever the solvent used **(Figure 1A & S1)**. However, the susceptibility to this insecticide varied significantly in *An. gambiae* field populations depending on the solvent used. The use of acetone combined with 1000ppm MERO® (81% Rapeseed oil methyl ester) as solvent, induced significant higher mortality compared to acetone or ethanol alone **(Figure 1A)**. A full susceptibility was observed for all the *An. gambiae* populations with a mortality rate of 100% when exposed to clothianidin dissolved in acetone+MERO at a concentration of 90 µg/ml **(Figure 1A)**. However, when exposed to clothianidin dissolved in acetone alone (150 µg/ml), the mortality varied from 51.1% ±15.2 in Nkolondom to 95.9% ± 2.6 in Njombe-Penja. On the other hand, when using Ethanol as solvent, the mortality varied from 11.4% ±4.6 in Nkolondom to 71.05% ± 6.9 and 89.3% ± 7.6 in Njombe-penja and Ndjilli (DRC) respectively **(Figure 1A).** The mortality with these two solvents increased significantly from 24h to 7days post-exposure confirming a slow-acting effect of this insecticide **(Figure S1, S2 & S3)**. The mortality rate was generally low for all the populations including Kisumu when exposed to acetone+Mero without insecticide confirming that MERO alone does not have a killing effect.

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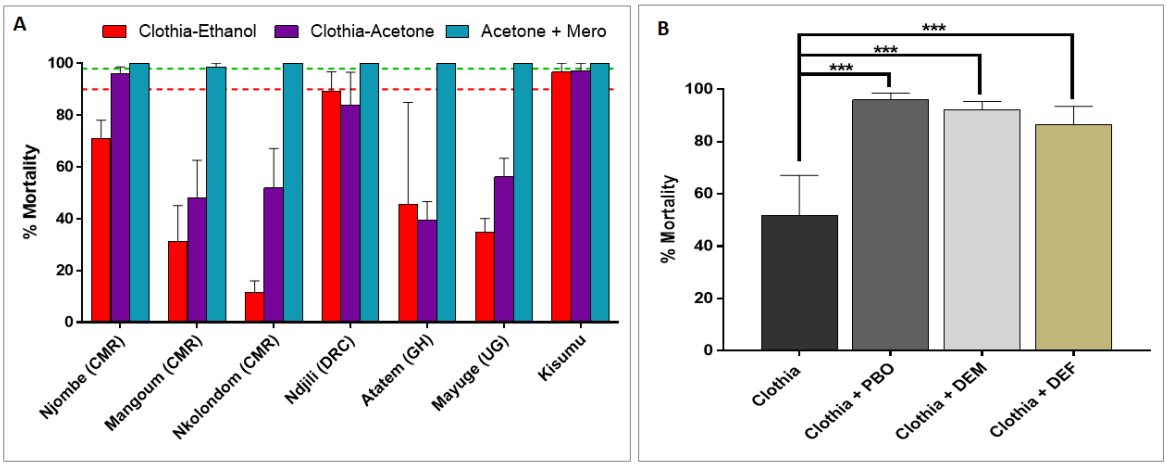

Figure 1: Susceptibility profile of *An. gambiae s.l* to clothianidin across Africa

(A)-Mortality rate of mosquitoes from various sites 7 days post-exposure to clothianidin dissolved in different solvents compared to the susceptible lab strain Kisumu. (B)-Effect of pre-exposure to synergist PBO, DEM and DEF against clothianidin on *An. gambiae* from Nkolondom. Results are average of percentage mortalities from four-five replicates each. The bars represent the standard error on the mean (SEM), linear color dots indicate the threshold for resistance (red) and susceptibility (green). CMR: Cameroon; DRC: Democratic Republic of Congo; GH: Ghana; UG: Uganda.

Synergist test with clothianidin

Susceptibility testing using PBO, DEM, and DEF as synergists revealed a significant recovery of susceptibility to clothianidin in Nkolondom population which showed the highest level of reduced susceptibility to this insecticide when diluted in ethanol or acetone alone **(Figure 1B)**. Mortality with clothianidin + PBO for Nkolondom population was 96.01 ± 2.6% versus 51.9 ± 8.5% for clothianidin without PBO pre-exposure (χ^2= 59.5; p < 0.0001). The same pattern was observed with DEM: DEM pre-exposure 92.1 ± 3.2% vs. 51.9 ± 8.5% for no DEM pre-exposure (χ^2 = 38.6; p < 0.0001) **(Figure 1B)**. Synergist bioassay with DEF also revealed significant recovery of susceptibility to clothianidin (DEF pre-exposure 86.4 ± 7.1% versus 51.9 ± 8.5% mortality without DEF pre-exposure (χ^2= 28.6; p < 0.0001) although this was slightly lower compared to PBO and DEM.

Susceptibility profile to Imidacloprid

The susceptibility to imidacloprid was evaluated on mosquitoes from Nkolondom and Mangoum (Cameroon), Atatam (Ghana) and Mayuge (Uganda). Higher mortality with this insecticide was observed in all the localities when using acetone+MERO as solvent. For the

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Nkolondom population, a mortality rate of 83.93% was observed with acetone + MERO compared to 65.29 ± 16.63% with acetone only (χ^2= 10.9; P=0.001) and 27.16% with ethanol (χ^2= 64.8; P<0.0001) sμggesting a likely resistance in this population **(Figure 2A)**. Similar pattern was observed for the Mangoum population where a mortality rate of 96.58% was observed with acetone + MERO compared to 27.71% with acetone only (χ^2= 100; P<0.0001) and 40.37% with absolute ethanol (χ^2= 72.8; P<0.0001) **(Figure 2A)**. For the population from Atatam, imadacloprid dissolved in Acetone + MERO induced 97.92% mortality and 57.16% when dissolved in acetone only (χ^2= 47.3; P< 0.0001). The mortality was very low when using absolute ethanol as solvent with mortality rate of 12.63% (χ^2 = 146; P<0.0001). Similar profile (96.1 % mortality vs 27.3%) was obtained for the population from Mayuge (χ^2= 99.6; P<0.0001).

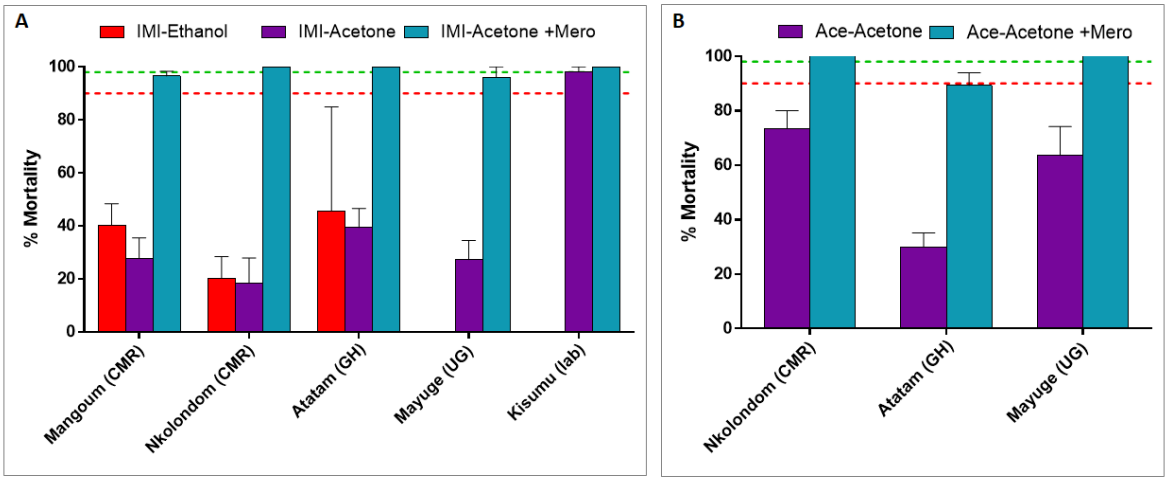

Figure 2: Susceptibility profile of *An. gambiae* s.l to imidacloprid and acetamiprid across Africa. Mortality rate of mosquitoes from different sites 7 days post-exposure to imidacloprid (A) and acetamiprid (B) dissolved in various solvents compared to the susceptible lab strain Kisumu. Results are average of percentage mortalities from four-five replicates each ± SEM. Linear colour dots indicate the threshold for resistance (red) and susceptibility (green). CMR: Cameroon; GH: Ghana; UG: Uganda; IMI: imidacloprid; Ace: acetamiprid.

Susceptibility profile to acetamiprid

When dissolved in acetone+MERO, acetamiprid also displayed greater efficacy compared to when dissolved in acetone only **(Figure 2B)**. For Nkolondom population, 100% mortality was obtained when using acetone and MERO compared to 73.5 ± 6.6% without MERO (χ^2= 30.4; P<0.0001). For Atatam population, 89 ± 4.6% mortality was obtained when using acetone and MERO compared

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to 30% without MERO (χ^2= 71.8; P<0.0001) **(Figure 2B)**. For Mayμge population, full susceptibility was noticed with MERO compared to 60% mortality without MERO (χ^2= 49.7; P<0.0001). These results sμggest that the level of reduced susceptibility to acetamiprid is higher in Atatam compared to other locations tested.

Diagnostic dosage of clothianidin using acetone and MERO as a solvent

Because of the very high mortality consistently observed with clothianidin dissolved in acetone + MERO, we decided to establish the diagnostic concentration using the susceptible lab strain Kisumu. The 24h mortality post-exposure to clothianidin ranged from 66.8% ±7.0 at 0.25μg/ml, 60.9% ±9.4 at 0.5μg/ml, 82.8% ±9.3 at 1μg/ml to 94.2% ± 3.6 at 2 μg/ml and 100% at 4μg/ml, 40μg/ml and 90 μg/ml **(Figure 3)**.

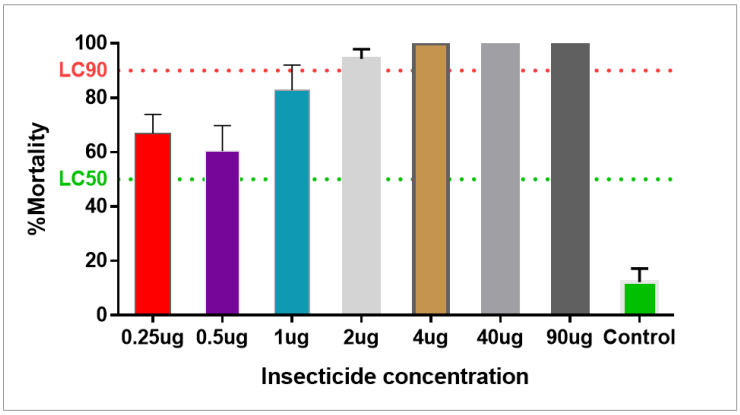

Figure 3: Assessment of diagnostic dose of clothianidin using acetone and MERO as solvent. Percentage mortality (24 h) of the susceptible lab strain Kisumu after exposure to each of the six concentrations of clothianidin (with acetone+MERO as solvent). LC50 represents the concentration able to kill 50% of mosquitoes and LC90 the concentration able to kill 90%.

Cross-resistance between clothianidin and pyrethroids

The distribution of L1014F-Kdr_w genotypes in mosquitoes alive after exposure to clothianidin was as follows: 24.1% (7/29) homozygous resistant (1014F/F), 27.6% (8/29) heterozygotes (L1014F-RS) and 55.17% (16/29) homozygous susceptible (L/L1014) **(Figure 4)**.

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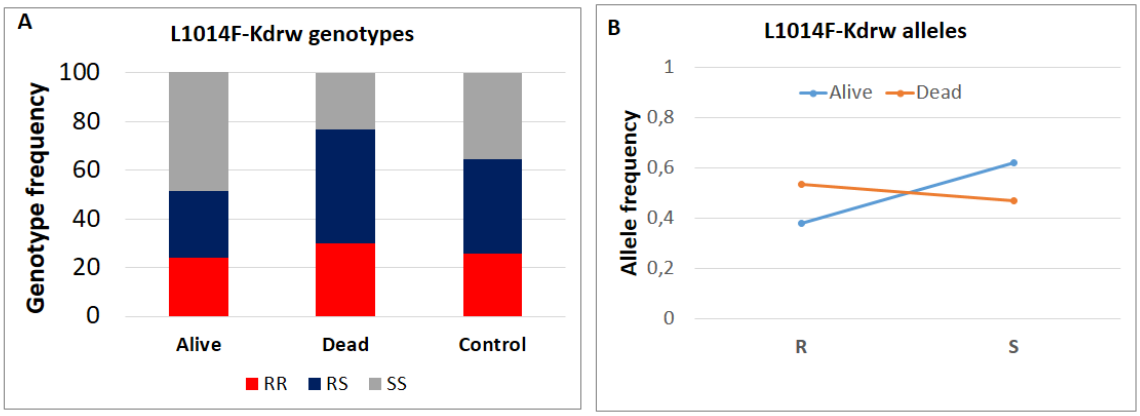

Figure 4. Association between the L1014F-kdr_w mutation and resistance to clothianidin.

Distribution of genotypes (A) and alleles (B) among the dead and alive mosquitoes after exposure to clothianidin. R represents the 1014F-resistant allele while S represent the L1014 susceptible allele.

In the dead mosquitoes, 30.0% (9/30) were homozygous resistant (1014F/F), 46.7% (14/30) were heterozygotes (L1014F-RS) whereas 23.3% (7/30) were homozygous susceptible (L/L1014). A significant difference was observed in the distribution of L1014F-Kdrw genotypes between alive and dead mosquitoes (χ^2=18.5; P<0.0001) with the homozygote resistant mosquitoes less able to survive (OR=0.5; IC 95%: 0.3–0.9; P=0.02) compared to the susceptible genotypes **(Table 1)**.

Table 1. Assessment of the association between L1014F-Kdr genotypes/alleles and the ability of mosquitoes to survive clothianidin exposure. SS: homozygote susceptible; RR: homozygote resistant; RS: heterozygote; (*) significant difference.

Genotypes	**L1014F-Kdr and clothianidin resistance**	
	Odds ratio	***p*-value**
RR vs. SS	0.3 (0.2- 0.7)	0,002**
RR vs. RS	1.4 (0.7- 2.8)	0.23
RS vs. SS	0.2 (0.1- 0.5)	<0.0001***
R vs. S	0.5 (0.3 –0.9)	0.02*

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In contrast, a significant difference was observed in the distribution of the I114T-GSTe2 genotypes between dead and alive mosquitoes and those with resistant allele had more ability to survive clothianidin exposure (χ^2=9.78; P=0.007) **(Figure 5)**.

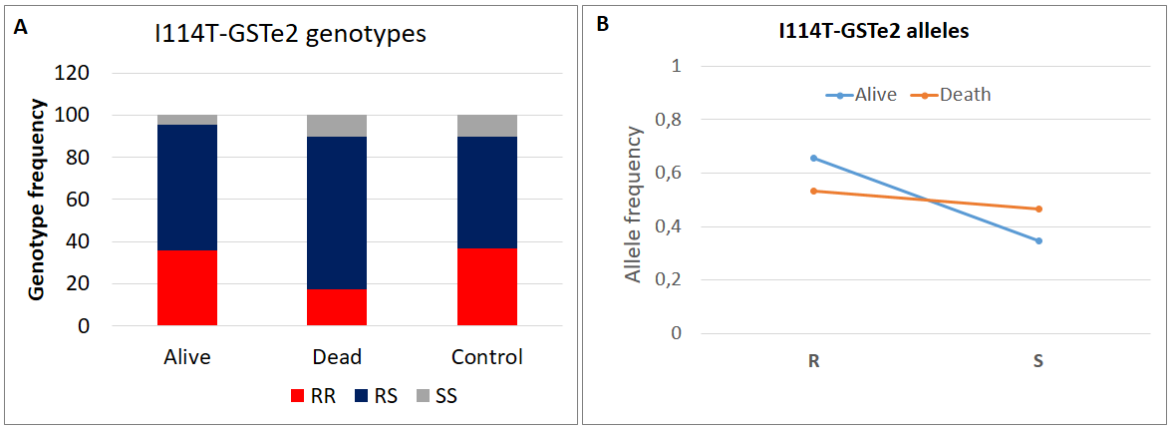

Figure 5. Association between the I114TF-GSTe2 mutation and resistance to clothianidin. Distribution of genotypes (A) and alleles (B) among the dead and alive mosquitoes after exposure to clothianidin. R represents the 114T-resistant allele while S represents the I114 susceptible allele.

The odds-ratio analysis confirmed that mosquitoes with the 114T resistant allele have a significantly greater ability to survive compared to those with the I114 allele as homozygous resistant mosquitoes were significantly more likely to survive clothianidin exposure compared to both heterozygote (OR=2.10; IC 95%: 1.11–3.97; P=0.013) and homozygous susceptible (OR=2.46; IC 95%: 1.15–5.26; P=0.012) mosquitoes **(Table 2)**. There was no significant difference between heterozygote and susceptible mosquitoes (OR=1.17; P=0.41).

Table 2. Assessment of the association between I114T-GSTe2 genotypes/alleles and the ability of mosquitoes to survive clothianidin exposure. SS: homozygote susceptible; RR: homozygote resistant; RS: heterozygote; (*) significant difference.

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Genotypes	I114T-GSTe2 and clothianidin resistance	
	Odds ratio	*p*-value
RR vs. SS	4.51 (1.3- 15.4)	0,0006**
RR vs. RS	2.5 (1.2- 4.9)	0.01*
RS vs. SS	1.8 (0.6- 5.6)	0.4
R vs. S	1.6 (0.9 –2.9)	0.05*

358

359 **4. Discussion**

360 The present study compared the efficacy of neonicotinoids in the major malaria vector *An.*
361 *gambiae* s.l across many African countries using three different solvents. Susceptibility testing
362 confirmed that neonicotinoids are slower-acting insecticides (when using acetone or ethanol alone)
363 compared to neurotoxic pyrethroids (17). While pyrethroids are characterized by rapid mortality of
364 mosquitoes within 24 hours, clothianidin/imidacloprid/acetamiprid dissolved in ethanol or acetone
365 alone induced mortality at 24h post-exposure was generally low (albeit highly variable) and
366 increased over days. Final mortality was recorded seven days post-exposure when using
367 ethanol/acetone alone as done previously (10). The mortality was low when using ethanol and
368 acetone alone and was the lowest in the population from Nkolondom, an area of intense agriculture.
369 The mortality rates of less than 20% with ethanol and less than observed in this locality support a
370 recent report of reduced susceptibility to neonicotinoids in the *An. gambiae* population from this
371 location (18). However, the addition of 1000ppm MERO® (81% Rapeseed oil methyl ester)
372 significantly increased the effect of these insecticides with 100% mortality for all the populations 24h
373 post-exposure even at lower concentrations. The low knock-down/mortality observed for all the
374 populations when using ethanol or acetone alone as a solvent could be linked to the crystallization
375 issue reported for neonicotinoids (19) preventing complete knockdown/mortality within 1-2h. The
376 use of MERO®, by preventing the crystallization, keeps the neonicotinoids for a longer period in a
377 soluble state and increases the reliability of the bottle assay. The low mortality observed with kisumu

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when exposed to acetone+Mero without insecticide, confirmed that MERO alone does not have a killing effect.

Despite the low mortality obtained with acetone or ethanol alone, a significant difference was observed between different populations with a mortality rate of 11-36% observed in Nkolondom, 31.07% in Mangoum 45.59% in Atatam and Mayuge compared to 71% in Njombe or 89.3% in Ndjili and 100% in Kisumu. This indicates that using ethanol or acetone alone might still be useful in capturing the variability between populations and even to detect those populations with reduced susceptibility and thus allow a better management of resistance. In contrast, using acetone plus MERO although more suitable in showing the full efficacy of neonicotinoids, might mask the selection of resistance in populations if not used at the right dose and could prevent the detection of resistance emergence. Therefore, to take advantage of the strengths of both protocols, it could be beneficial to monitor the susceptibility profile to neonicotinoids using acetone (or ethanol) alone and also acetone plus MERO. Because the dose of 90µg/ml as recommended by Bayer or 50µg as determined recently in Ivory coast is very high for monitoring of resistance, one option could be to reduce this dose to a level that allows for assessing the efficacy of neonicotinoids while monitoring resistance development. In this study we observed that the concentration of 8-10µg/ml could be used for monitoring of resistance to clothianidin as 4µg was the minimum concentration giving 100% mortality with the susceptible lab strain Kisumu.

Cross resistance between Pyrethroid and neonicotinoid

A negative association was observed between the 1014F-kdr allele and resistance to clothianidin. Such negative association could be attributed to the deleterious effect of kdr or other related genes in the presence of clothianidin, for which the vgsc is not the target. Accordingly, a gradual decrease of kdr-resistant homozygote mosquitoes was observed during the clothianidin selection process by Zoh et (2021) and this could explain the negative correlation observed in this study between kdr and clothianidin resistance. This is the first time such negative association is observed between pyrethroid resistance mechanism and insecticides with different mode of action.

Synergist assay using PBO and DEF also revealed significant recovery of susceptibility to clothianidin showing that monoxygenases, GSTs and esterases are all involved in clothianidin resistance. Over expression of P450s monoxygenases was frequently reported in many resistant cases

such as in *An gambiae* recently where a strong selection signature associated with clothianidin selection was observed on a cytochrome P450 gene cluster with the gene CYP6M1 showing the highest selection signature together with a transcription profile supporting a role in clothianidin resistance. Overexpression of P450s were also mentioned in *M. persicae* (20), *Bemisia tabaci* (21-23), *Trialeurodes vaporariorum* (24), *Nilaparvata lµgens* (25), *Leptinotarsa decemlineata* (26) and many other pests (27).

For the first time, we observed in this study a significant correlation between *GSTe2* and clothianidin resistance in *An. gambiae* indicating that *GSTe2* could metabolise or could be involved in phase 2 conjµgation of metabolite of clothianidin degradation. This was confirmed by the synergist test with DEM which resulted in recovery of susceptibility to clothianidin. Since *GSTe2* is also a pyrethroid/DDT resistance gene, its association with clothianidin resistance indicates that clothianidin-based tools could rapidly lose their efficacy in areas of high *GSTe2*-based metabolic resistance. However, future studies are needed to establish the role of *GST* or specific mechanisms such as esterases and P450s in clothianidin resistance.

5. Conclusions

This study investigated the susceptibility of the major African malaria vector *An. gambiae* to neonicotinoids using three different solvents and evaluated potential cross resistance between pyrethroid resistance markers and clothianidin survival. The study revealed that the use of acetone or ethanol alone as a solvent for clothianidin bioassay can over-estimate the level of resistance in mosquitoes due to crystallisation. Furthermore, we showed that the use of clothiandin dissolved in acetone + MERO display very strong efficacy with 8-10µg/ml as diagnostic dose for monitoring of resistance to clothianidin but could mask the development of resistance. We recommend monitoring the susceptibility using both acetone alone and Acetone+MERO to capture the accurate resistance profile of the mosquito populations.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1,

Figure S1: Mortality rate of the susceptible lab strain Kisumu to clothianidin (A) and Imidacloprid (B) using the three solvent. The bars represent the standard error on the mean (SEM).

Figure S2: Mortality rate of wild *An. gambiae* s.l from central Africa to clothianidin using the three solvent. The bars represent the standard error on the mean (SEM).

Figure S3: Mortality rate of wild *An. gambiae* s.l from Western and Eastern Africa to clothianidin using the three solvent. The bars represent the standard error on the mean (SEM).

Author Contributions: C.S.W. conceived and designed the study; M.T, LMJM, B.D.M, D.N.N, collected the samples with the help of J.K, F.W, E.Z.M., and M.O.; M.T., T.A, and W.T, maintained the strain in the insectary and performed bioassays; M.T. and T.A performed the molecular analyses; M.T, and C.S.W. analyzed the data; M.T wrote the manuscript with contributions from and C.S.W., J.K, F.W, E.Z.M., and M.O.. All authors read and approved the final manuscript.

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