Human and plant volatiles; lures for mosquito, vectors of dengue virus and malaria. A review

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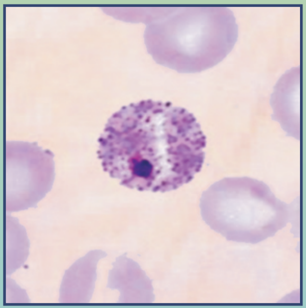

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Review Articles

Human and plant volatiles; lures for mosquito, vectors of dengue virus and malaria

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ABSTRACT

Increased outbreaks of mosquito borne diseases like the deadly parasitic disease, malaria and arboviruses like Zika, yellow fever and dengue viruses around the world have led to increased interest in traps that could effectively be used against mosquitoes. For example, a Google search at the time of this writing, asking, 'which is the best way of trapping mosquitoes?' produced 35.5 million search results. Regardless of the interest in the subject, scientists have yet to find a definitive answer to these questions. One area that has been exploited as a potential source of efficient traps for mosquitoes is host odour baits. Since mosquitoes are attracted to their hosts through odours produced by the hosts, it's highly likely that synthetic chemical blends based on host odours could provide a solution. Most mosquito species have 2 hosts: vertebrate animals and vascular plants. Amongst the vertebrates, most diseases spread by mosquitoes are to humans. Considerable research has therefore been conducted on human odours that elicit attraction in mosquitoes, with emphasis on compounds from sweat and skin. Interest on plant volatiles is currently gathering pace because unlike human odours that only attract host seeking female mosquitoes, plant odours can attract both male and female mosquitoes of all gonotrophic stages. This review article concentrates on some of the chemical compounds in human and plant host odours that have shown a potential as attractants to mosquitoes especially *Aedes aegypti* and *Anopheles gambiae s.l.*

INTRODUCTION

Mosquitoes and other blood sucking insects are of great economic importance in the world today as they spread deadly diseases like malaria, yellow fever, dengue, Zika and chikungunya viruses. Among the vectors, *Anopheles gambiae s.l* and *Aedes aegypti* are of significant medical importance. While malaria transmitted by *An. gambiae s.l* infects 228 million people per year and kills 405,000 people per year[1,] arboviruses like yellow fever, Zika virus, chikungunya fever and dengue fever transmitted by *Ae. aegypti* are similarly causing huge morbidity and mortality to human populations. It is feared that over 3.9 billion people worldwide are currently at risk of dengue virus[2]. The World Health Organization reports that there may be 100–400 million dengue infections in the world annually[2]. To exacerbate the problem, apart from yellow fever, there is currently no treatment or universal licensed vaccine against the other diseases transmitted by *Ae. aegypti.* Whereas vaccines like Dengvaxia® (CYD-TDV) have been developed and licensed against dengue infection, it has been reported to pose a risk of severe dengue in seronegative patients and is thus not recommended for use in children less than 9 years old[2]. This leaves vector control as a major method for control and prevention of these diseases.

A lot of effort has therefore been made to develop devices to attract and capture mosquitoes especially *Ae. aegypti and An. gambiae s.l* in the field[3–6]. The aim is to use such tools for surveillance and control of mosquitoes through mass trapping, push-pull as well as lure and kill strategies[3–6]. These devices include traps with visual[7] and olfactory cues mainly derived from host odor as baits[8].

Considerable research has been conducted on identifying mosquito attractant chemical compounds in human host sweat and skin odor[9–19] with an overall goal of developing synthetic odor blends that would out-compete the attractive power of humans, thereby leading mosquitoes away from their preferred host and breaking disease transmission[20–24].

Varying success has been reported. While some authors found that their optimal blends could not compete with natural skin emanations[23], others found their blends to be at par with host skin odour in attracting *Ae. aegypti*[23] and *An. gambiae*[22] whereas others found theirs to be more attractive than humans to the malaria vector *An. gambiae s.l*[20–21]. One such blend to be reported is the Mbita blend 5 (ammonia + L-lactic acid + tetradecanoic acid +3-methyl-

1-butanol augmented with 2-butanone) which was used successfully in mass trapping of malaria vector *An. gambiae s.l* leading to a reduction of malaria prevalence in areas of intervention in Rusinga island, Kenya[24].

In addition to human odour, efforts have been made to understand the chemical mediation in mosquito–plant interactions and to explore the opportunity presented by this unique behaviour for development of new vector control tools. The advantage of phytochemicals is that they have the potential of attracting both male and female mosquitoes of diverse age groups and varying gonotrophic stages[25] unlike human host odour baits which target mainly blood seeking female mosquitoes. However, potential challenges to their successful use are the abundance of competing volatiles, narrow plant-host specificity, and a weaker behavioural response to phytochemical cues[25].

This review concentrates on human odor that has been tested in attracting mosquitoes with the hope of developing a bait for trapping especially *Ae. aegypti* and *An. gambiae* in the field. The review also emphasizes mosquito attractant plants, plant attractant compounds and plant volatiles that have been used as lures to trap and kill mosquitoes.

Human host volatiles

To orient toward hosts, female mosquitoes seeking a blood meal detect a variety of chemical and physical cues including body odor, carbon dioxide (CO_2), moisture, heat, and visual contrast[26]; Gibson and Torr, 1999[26–29]. Of these sensory cues, ~4% CO_2 exhaled in breath is a potent behavioral activator and attractant for mosquitoes and is often considered to be the most important sensory cue used by these disease vectors to find humans[30]. Smith *et al.* 1970[9] reported the enhanced attraction of mosquitoes to sweat in conjunction with CO_2 and concluded that other components of human odor may be involved as well. Subsequently, the role of other chemical compounds in human host odor as mosquito attractants has been examined in detail[31–42] leading to the identification of over 300 chemical compounds in human skin odour[12–13, 19, 31–42] . These compounds mainly fall within seven groups; Aldehydes, organic fatty acids, ketones, alcohols, aliphatic aromatics, esters and amines/amides.

Carbon dioxide

The attractive power of CO_2 to mosquitoes was discovered in bioassay experiments by Rudolfs, 1922[43] who observed that small quantities of the gas led to activation of the insects, and that human expiration, caused the insects to display pleasure and a directed flight and probing of the emitting source. Consequent investigations noted that in a broad range of mosquito species, CO_2 elicits a suite of context-dependent effects that promote host-seeking behavior[43–46]. Filamentous intermittent plumes of CO_2 in the region of 0.01% above background have been reported to elicit stereotyped and sustained patterns of upwind flight toward the CO_2 source in female *An. gambiae*[44] in *Ae. aegypti*[46] and *Cx. quinquefasciatus*[45]. However, carbon dioxide alone emitted at a rate equivalent to that released by the human bait is less attractive than human baits[47].

Due to its role as a flight activator and in sharpening attraction of human skin volatiles to mosquitoes, carbon dioxide has widely been used in mosquito traps , including the BG-Sentinel trap[48] Counter Flow Geometry trap/ MMX trap[49–50] and CDC light traps[51] in disease surveillance programs. It is normally released through tanks[43–47], frozen ice[9–20], fermented molasses or sugar[52].

Although carbon dioxide alone has been reported to be more efficient in some instances in catching mosquitoes in the field[53,] studies on malaria vectors, *Anopheles spp.*[22, 51] and *Ae. aegypti* (L)[19, 29, 45] reported that it was insufficiently attractive as a standalone bait. Better catch rates were obtained when using CO_2 in combination with other host attractant odor like lactic acid, water vapor and human sweat[54–61].

Lactic acid

Humans have uniquely high levels of skin-borne lactic acid[9, 12–15, 37–42] as compared to other mammals and birds[40] which has been associated with strong attraction of anthropophilic mosquito species; *An. gambiae*[9, 37, 40] and *Ae. aegypti* [9, 11, 31, 33–34]. The addition and removal of lactic acid from human skin extracts respectively increases and decreases attraction of *Ae. aegypti*[11, 31] and *An. gambiae*[34]. Similarly, lactic acid also appears to contribute to host specificity in tsetse fly[62]. The combination of lactic acid with ammonia[23, 36, 63] and fatty acids of various chain lengths (64) and carbon dioxide creates a powerful attractive synergism[9, 31, 61, 65–66] as do other compounds from human skin, namely, dimethyl disulfide, and acetone[12–13, 35]. This synergistic effect of lactic acid has led to it being used as a component in most human volatile derived blends targeting various mosquito species. For example, in the BG lure, a synthetic odour bait popularly used to trap *Ae. aegypti* in the field for surveillance[19]. has lactic acid as its major chemical component[8] whereas attractive odour baits for sampling the malaria vector *An. gambiae* also have lactic acid as a major component[20–22]. It is important to note that a blend of lactic acid is also attractive to other hematophagous insects like Triatomine bugs that feed on man[67]. However, lactic acid on its own is much less attractive than whole human odor extracts[11, 61, 67] and in some instances, lactic acid has been reported to have antagonistic, repellant and negative effect on trap collections of *Aedes vexans*[65], *Aedes nigripalpus*[68] and *Culex sp*[66].

It can therefore be stated that the response to lactic acid alone or when combined with other kairomones is dose dependent[11, 63, 69] and depends also on the species of the mosquito[66, 68, 70]. Lactic acid has also been reported to attract at a distance, but to repel at short range and thus has a negative influence on *Ae. aegypti* attraction in close proximity to a host[53]. These results underscore the fact that attractants available commercially are not universally attractive to all mosquito species, and considerations need to be made about the target species and their propensity for attraction to the compound(s) released from the lures.

Ammonia

Ammonia is a typical animal excretory product found on the skin of all vertebrates. Just like lactic acid, ammonia is present on human skin as well as in breath and is attractive at doses where it's supposed to evaporate from a human host[8, 9, 15, 36, 63, 71]. Ammonia on its own is attractive to the malaria transmitting mosquito, *An. gambiae s.s*[3, 11, 15]. However, ammonia alone or in combination with carbon dioxide has been reported to be not attractive to *Aedes aegypti*, but the addition of lactic acid increases its attractiveness[64, 72]. On the other hand, no synergistic effect was witnessed when ammonia was combined with lactic acid to *An. gambiae*, but addition of third compound, carboxylic acid, led to synergistic effect[11].

Ammonia has thus been incorporated in synthetic odour blends used in trapping anthropophilic *An. gambiae s.l*[20, 22–23]. The Mbita blend 5 which consists of ammonia + L-lactic acid + tetradecanoic acid +3-methyl-1-butanol + carbon dioxide/butanone has been used successfully in mass trapping of malaria vectors in Rusinga island in western Kenya[24]. The synergistic effect of ammonia with other attractant compounds has also been observed in other insects. Addition of ammonia to a trap baited with CO_2 increased the trap catch of "canyon flies" (Fannia conspicua Malloch), which are not typical blood feeders, by 89.9% over CO_2 alone[72].

Alcohols

Alcohols are widely known to repel mosquitoes. For example, citronellol (3,7-imethyl--octen-1-ol), and its related aldehyde analog, citronellal exhibits spatial repellence of *Aedes aegypti* in laboratory bioassays.

Octenol

Octenol found mainly in bovine breath[73] and human breath and sweat[74] had been first reported to be a potential attractant for mosquitoes in several studies that have investigated its use in a variety of habitats and for a range of mosquito species[68, 73–80]. It has been suggested to have species-specific effects and response to it also varies geographically, seasonally, and according to the physiological state of the mosquito[81].

It is attractant for only a few mosquito species[53, 75] and catch rates only increase when it is in combination with other attractants especially, carbon dioxide. Octenol does not appear to be a strong attractant for *Aedes aegypti* and was reported to significantly decrease collection of *Ae. aegypti* by 50% in laboratory and 100% in the field[53]. Laboratory tests revealed that octenol repelled *Ae. aegypti* even when used in combination with carbon dioxide. Similarly, it is not a potent attractant to *Ae. albopictus,* another member of the stegomyia just like *Ae. aegypti*[77]. It has been suggested that the negative effect of octenol on *Ae. aegypti* attraction is possibly due to octenol being a product of rumination yet *Ae. aegypti* is a highly anthropophilic mosquito and, as such, probably has had little interest in bovines. Octenol has also been isolated from many plants and fungi[81], and it is therefore expected that any mosquito not usually attracted to omnivorous or semi-omnivorous vertebrates will not be attracted to octenol. Probably for the same reasons octenol even though it elicits electrophysiological reaction in *An. gambiae*[16] is similarly not a good attractant to this highly anthropophilic mosquito[76]. The lack of attraction to octenol has also been demonstrated in Culex mosquitoes[68,77]. However, some mosquito species like A*nopheles (Kerteszia) sp* seem to be attracted to octanol[78].

Apart from mosquitoes, olfactory effect of octenol and other alcohols has been observed in other insects. The alcohols, 1-octen-3-ol and 1-nonanol induced a clear concentration-dependent activation and attraction response in sand flies females[79]. Also, octenol (1-octen-3-ol) is an ingredient in "synthetic ox-odour" which has been used successfully as an odour bait in tsetse fly traps[80]. Other alcohols that have also shown the potential to be used as attractants for mosquitoes apart from octanol are 3-methyl-1-butanol which showed significant synergistic effect with a standard blend consisting of ammonia, (S)-lactic acid, tetradecanoic acid, and carbon dioxide to *Anopheles gambiae* in olfactometer[73] and both semi field and field conditions in western Kenya[21]. However, 3-methyl-1-butanol alone might not be a good lure for malaria vectors[74]. Dodecanol also showed synergistic effect with ammonia and lactic acid[22] while other alkenols like 4-penten-2-ol and 2-decen-4-ol have been reported to be more attractant to *Culex sp* mosquitoes than octanol[82].

Aldehydes

It has been hypothesized that aldehydes may play a role in the commonly observed differential attraction of anthropophilic mosquitoes *Ae. aegypti*[83] and *An. gambiae*[84] to different individuals. Higher amounts of aldehydes have been associated with higher attractiveness of individuals to mosquitoes[83–85]. It has also been reported that individuals infected with malaria have greater amounts of aldehydes like heptanal, octanal, and nonanal making them more attractive to the malaria vector *An. gambiae* than the uninfected[84]. Addition of aldehyde heptanal to healthy human odour blend increased their attractiveness to the malaria vector *An. gambiae*[84]. The differential attraction of *Cx. quinquefasciatus* to humans has also been linked to the aldehyde mixture ratio between individuals where the mixtures in the attractant individuals were found to be different from the mixtures in the non-attractant individuals Leal *et al*., 2017[85]. However, Logan *et al*., 2008[83], associated 3 aldehydes; octanal, nonanal, decanal together with ketones; 6-methyl-5-heptan-2-one (6-MHO) and geranylacetone (GA) with people who were less attractive to *Ae. aegypti*.

Some aldehydes, 2-nonenal[40] and nonanal[43,] on human skin have even been used to differentiate between different ages[40]. Men older than 39 years were reported to have larger amounts of 2-nonenal, that imparts an unpleasant ‘ageing odour’ than younger men[40]. Olfactory effects of aldehydes on mosquitoes have also been confirmed with electrophysiological studies on *Ae. aegypti*[19, 86] and in *Cx. quinquefaciatus* mosquitoes[87]. Apart from attraction of mosquitoes to humans, aldehydes have been reported to be responsible for attraction of mosquitoes to birds too[88–89].

Carboxylic acids

Fatty acids are present in significant amounts in human skin odour[19, 42, 90]. Attractivity of *Ae. aegypti* to carboxylic acids has also been reported for the yellow fever vector *Ae. aegypti*[19, 22]. A weak attraction of *Ae. aegypti* to a blend of several aliphatic and amino acids was reported in 1961[83] and the attractiveness is enhanced when presented together with CO_2. It has also been reported that the attractive effects of fatty acids in host finding of anthropophilic *Ae. aegypti* depends on two factors: their chain length and their specific combination in the blend[91]. The most attractive carboxylic acids are of two groups: C_1–C_3 (short chain) and C_5–C_8 (Long chain). Addition of lactic acid and ammonia to an unattractive augment the attraction. However, longer chain fatty acids (C_{13}–C_{18}) were less attractive to *Ae, aegypti*, and fatty acid C_{14}, which is the most abundant in human sweat[92] and C_{11} even reduced the attractiveness of any combination of lactic acid with another fatty acid. These findings point in a direction similar to those reported by Skinner *et al.*,[93–94] who found a repellent effect of skin-surface lipids.

Fatty acids have also been reported to be attractive to *An. gambiae* and to play an essential role in host-seeking behavior[16, 23] and their contribution to blend attractiveness depends on the specific compound studied. While carboxylic acids like propanoic acid, butanoic acid, 3-methylbutanoic acid, pentanoic acid, heptanoic acid, octanoic acid, and tetradecanoic acid have been reported to increase attraction of a mixture of lactic acid and ammonia such that in the absence of tetradecanoic acid led to the blend being repellent, 3-methylbutanoic acid had a negative effect on trap entry response. Isovaleric acid on the other hand was reported to cause an inhibitory effect when added to a standard blend consisting of ammonia, (S)-lactic acid, tetradecanoic acid, and carbon dioxide in *An. gambiae.*

Ketones

Amongst the ketones, acetone which just like carbon dioxide is a major component of breath, has been found to attract *Aedes aegypti (L.)* in olfactometer bioassays and blends consisting of L-lactic acid and acetone have been reported to have attraction similar to L-lactic acid and carbon dioxide[35]. Acetone has also been demonstrated to be an attractant to *An. gambiae* and *An. stephensi*. Liston and synthetic blends of acetone and other compounds have also been used to successfully trap mosquitoes in the field[95].

Butanone, another ketone, has shown promising results in attracting host-seeking malaria vectors *An. gambiae s.l.* and *An. funestus* under field conditions and has also been postulated to serve as a good replacement for CO_2 in synthetic blends targeting these vectors. This postulation is supported by two separate electrophysiological studies that have reported that the olfactory receptor cell of the fruit fly *Bactrocera tyoni* that responds to CO_2 also responds to 2-butanone[96]. Further, 2-butanone has been reported to induce a dose-dependent activation of the CO_2 receptor neuron in the maxillary palps of *An. gambiae, Ae. aegypti* and *Cx. quinquefasciatus*[97].

However, other ketones are generally known to be mosquito repellants. 6-methyl-5-heptan-2-one (6-MHO) and geranylacetone (GA), have been observed to be natural repellents to *Cx. quinquefaciatus* at higher doses and may account for differential attraction in different ratios[85]. 6-methyl-5-heptan-2-one (6-MHO) and geranylacetone (GA) were named as inhibitors/repellants against the attraction of *Ae. aegypti*[83] whereas ketones of C7-C12 molecular chain length (optimum in the C8-C10 range) suppressed or inhibited attraction of *Ae. aegypti* in a triple cage olfactometer bioassay[28]. It has been reported that (6-MHO) elicited no electrophysiological reactions in *Cx. quinquefaciatus*[83].

Other human odour-based mosquito attractants

Other human-associated chemical compounds important in host location include dimethyl disulfide and dichloromethane for *Ae. aegypti*[35]. Selected dilutions of butan-1-amine, 2-pentadecanone, and 1-dodecanol increased the proportion of *An. gambiae s.l*, *An. funestus*, and Culex caught in traps containing Mbita Blennd (ammonia + L-lactic acid + tetradecanoic acid +3-methyl-1-butanol + carbon dioxide). However, 4, 5-dimethylthiazole caused an inhibitory effect on *An. gambiae* when added to the Mbita blend even more so, when added together with isovaleric acid[21]. Similarly, in the absence of CO_2, addition of three concentrations of butan-1-amine caused inhibition to attraction of *An. gambiae* when added to the blend.

Mosquito attraction to plant volatiles

Most mosquito species have two hosts: vertebrate animals and vascular plants. The blood meal from vertebrate hosts contributes energy for survival and flight, in addition to its role in allowing egg development in anautogenous mosquitoes. Sugar meals on the other hand provide the necessary energy for both survival and flight during the mating period and until the female can find vertebrate blood[25, 98–99]. Sugar feeding is therefore a fundamental characteristic of a mosquito's life. Most evidence indicate frequent ingestion of plant sugar, usually as floral and extrafloral nectar and honeydew, by mosquitoes of both sexes and all ages[25, 100].

Just like for their vertebrate hosts, the plant sugar sources are located by orientation to visual and chemical cues associated with the presence of sugar[25.] Therefore, it's possible that these stimuli can be put to use, either in monitoring or controlling mosquito populations, provided that they attract large numbers to traps.

However, while the kairomones involved in attracting mosquitoes to their vertebrate host have extensively been studied and identified, the need to intensify the characterization of semiochemicals used by mosquitoes to find their plant hosts for sugar is excellant. The principal advantages of phytochemical attractants are that they lure a) both sexes, b) all ages, including those that are newly emerged, c) females in all gonotrophic states, and d) both nondiapausing and reproductively diapausing females[25, 99–100]. Potential challenges to their successful use are the abundance of competing volatiles, narrow plant-host specificity, and a weaker behavioral response to phytochemical cues.

The potential for plant volatiles to lure mosquitoes was first reported in the 1960s. It was reported that various mosquito species in the field were attracted to light-colored flowers with distinct fragrances. Subsequently, studies on plant-mosquito interactions have shown that floral nectar forms an important component of both male and female mosquito diet[25, 99, 101–104.] In the recent past, it has been observed that plant odours and synthetic plant odour blends are attractive to *An. gambiae*[51, 104–105] and *Ae. aegypti*[103] in olfactometer and field bioassays. *Ae. aegypti* mosquito was observed to prefer landing on the plant *Lobularia maritima (L.)* Desv. (Brassicaceae) when compared to *Plectranthus neochilus Schltr.* (Lamiaceae), *Tagetes patula* L. [Asteraceae and freshly cut inflorescences of *L. maritima* elicited a positive flight response in both sexes (male and female)]. Amongst the volatiles found in *L. maritima* static head space, acetophenone was attractive and 1-octanol caused a flight aversive response to *Ae. aegypti*[104]. A solution of guava and mango nectars was shown to be a promising lure candidate for male *Aedes aegypti* in an attractive toxic sugar bait-based (ATSB) tests[103]. The solution performed significantly better than floral-based attractants phenylacetaldehyde, linalool oxide, phenylethyl alcohol, and acetophenone previously identified.

Odours released by plants; *Parthenium hysterophorus, Bidens pilosa* (Asteraceae) and *Ricinus communis* (Euphorbiaceae (Asteraceae), were also shown to be significantly more attractive to the malaria vector *An. gambiae* than the control (solvent only) in olfactometer assays[102]. *Parthenium hysterophorus* released the most attractive volatiles while *Bidens pilosa* (Asteraceae) volatiles were the least attractive. Out of the 15 EAD-active components identified from the three plants, six: hexanal, β-pinene, limonene, (E)-β-ocimene, (E)-linalool oxide and (E)-β-farnesene were observed to be attractive to *Aedes aegypti* either singly or in blends. A blend of all the six at high concentrations (hexanal, β-pinene, limonene, (E)-β-ocimene, (E)-linalool oxide and (E)-β-farnesene) was significantly more attractive than volatiles of by *P. hysterophorus*, the most attractive plant[102].

Consequent field evaluations of the attractive blend [(*E*)-linalool oxide, (*E*)-β-ocimene, hexanal, β-pinene, limonene, and (*E*)-β-farnesene] showed that these plant volatile based blends compared favorably with human volatile based blend comprising heptanal, octanal, nonanal, and decanal and worn socks in trapping malaria vectors under semi field and field conditions[50].

In yet another study, a plant-derived 3-component blend of (*E*)-linalool oxide, β-pinene, β-ocimene also compared favourably to human derived 4-component blend comprising heptanal, octanal, nonanal, and decanal in olfactometer bioassays[105]. However, when the plant and human odour blends were combined, fewer females of *An. gambiae* were attracted than with the individual blends. In contrast, a dose-dependent effect was observed when the plant and human volatile blends were combined in field trials. Significantly improved trap catches were witnessed at higher doses[105]. These results highlight the potential of plant-based odors for the surveillance and mass trapping of malaria vectors.

Several other studies have also reported the attractiveness of flowers and/or fruits/pods to wild *An. gambiae*[106–107] *Aedes albopictus*[108–109] *Ae. aegypti*[15, 118–119]. Laboratory assays have also shown that floral and vegetative scents play a vital role in the attraction of other mosquitoes for example *Culex pipiens pipiens* which was demonstrated to be attracted to *L. vulgare, A. meillefolium, Aselepias syriaca and Solidago canadensis*[99]. Attraction of *Ae. mcintoshi* and *Ae. ochraceus* and to five plants including *Pithecellobium dulce* (Fabaceae), *Opuntia ficus-indica* (Cactaceae), *Leonotis nepetifolia* (Lamiaceae), *Senna alata* (Fabaceae) and *Ricinus communis* (Euphorbiaceae) has also been reported[107.]

The response of mosquitoes to plant odours has further been confirmed by electrophysiological tests where mosquito antennal response to plant-related odours have been demonstrated. A study identified a total of 21 *Ae. aegypti*, *Ae. mcintoshi* and *An. gambiae* antennally-active components from host plants *(Pithecellobium dulce* (Fabaceae), *Opuntia ficus-indica* (Cactaceae), *Leonotis nepetifolia* (Lamiaceae), *Senna alata* (Fabaceae) and *Ricinus communis* (Euphorbiaceae)[107]. Whereas *Ae. aegypti* predominantly detected benzenoids, *Ae. mcintoshi* detected mainly aldehydes while *An. gambiae* detected sesquiterpenes and alkenes. Interestingly, the monoterpenes β-myrcene and (*E*)-β-ocimene which were consistently detected by all the mosquito species were also found to be present in all the identified host plants suggesting that they may serve as signature cues in plant location[107].

In addition to *An. gambiae*[102], plant volatiles (*E*)-β-farnesene and (*E*)-linalool oxide have been shown to elicit electrophysiological and behavioral responses in the western flower thrips, *Frankliniella occidentalis*, while phenylacetaldehyde has been shown to be attractive to the cabbage butterfly, *Pieris rapae*, and the cotton bollworm, *Helicoverpa armigera*[110]. *Ae. aegypti* and *Ae. triseriatus* were also shown to respond to *o*-cresol and related compounds[110–111, 123].

Electrophysiological responses have also been demonstrated in *Culex sp* mosquitoes with a group of terpenes (thujone, verbenone, α-pinene, citral, nerol, limonene, and farnesol), green leaf volatiles (hexanal, 1-hexenol, and (*Z*)-3-hexen-1-ol,) and fatty acid esters (ethyl propanoate, methyl propanoate, ethyl butyrate and ethyl acetate) shown to both broadly- and narrowly-tune antennal receptor neurons in *Cx. Pipiens*[112]. Antennal responses of *Cx. pipiens* and *Ae. aegypti* to 14 compounds of *Silene otites* (L.), a plant pollinated by moths and mosquitoes has also been demonstrated[109]. Further behavioural bioassays with *Cx. pipiens* showed that 14 compounds were attractive out of which four compounds; acetophenone, linalool oxide (pyranoid), phenyl acetaldehyde and phenylethyl alcohol were the most attractive while hexanol was the least, a dual choice olfactometer bioassays showed that a mixture of the four most attractive compounds was more attractive than a mixture of all the 14[107].

A consequent study showed that 12 electrophysiologically active compounds were common amongst nine different populations of *Silene otites* (L.). Out of the 12, Linalool oxide (furanoid) and linalool evoked the strongest electrophysiological responses in male and female mosquitoes whereas and (Z)-3-hexenyl acetate was strongly active in females. Medium responses were evoked in males by (Z)-3-hexenyl acetate while benzaldehyde and methyl salicylate evoked the same in females. Lilac aldehyde, lilac alcohol, and linalool oxide (pyranoid) evoked medium responses in in both sexes[113].

Some of these compounds like benzaldehyde which is a major constituent of floral scent been attributed to the attraction of *Cx. pipiens* to *Asclepias syriaca* (Asclepiadaceae) together with phenylacetaldehyde and (*E*)-2-nonenal[99]. On the other hand, Linalool oxide, lilac aldehydes and lilac alcohol are isomers derived from oxidation of linalool. These isomers have been associated with the fragrance of various plants and have been shown to elicit electrophysiological activity in the noctuid moth, *Hadena bicruris*, which is known to rely on lilac aldehydes to locate its host plants[114]. Their detection by various mosquito species highlights the significance of this group of plant compounds in insect-plant interactions.

Potential application of human odours and phytochemicals in mosquito vector management

Increase in the transmission of mosquito borne diseases like malaria and dengue fever has raised doubts on the efficacy of the currently available vector control tools. Resistance has developed against insecticides rendering Insecticidal Residual Spraying (IRS) and Long Lasting Nets (LLNs) ineffective against malaria control[115–117]. Adulticidal fogging aimed at *Aedes* mosquitoes has also not been effective as *Aedes* tend to rest in secluded sites[15].

This has necessitated exploration of novel intervention measures that could augment or even replace the non-effective methods. Push pull system, a strategy already used successfully in integrated crop pest management[118–119] is now being considered for mosquitoes[6, 24, 120]. The idea is to use push components, such as spatial repellents, to keep mosquitoes away from human dwellings and trapping systems baited with attractant lures to remove mosquitoes from the intervention area. The push pull system has been used against anthropophilic *An. gambiae* and *Ae. aegypti* with quite some success. It was used in a malaria endemic zone in western Kenya to reduce *An. gambiae* house entry by more than 50% in intervention areas[5] and consequently reduce malaria by 29.8% compared to non-intervention areas[121]. An odour baited push pull system has also been tried for the vector of dengue virus *Ae. aegypti* [119] where *Ae. aegypti* landing collections were significantly reduced by 50% in laboratory experiments.

How the Push Pull system could be improved

These push pull systems could be improved further by research on suitable repellent concentrations and by improving the baits to capture more target mosquitoes. Screening of eaves and/or ceilings, which has already proven to be an effective measure against mosquito house entry[120] could also incrementally improve the efficacy of the push and pull systems in the villages. Odour-baited traps are therefore likely to be complementary to other novel intervention strategies, such as LLNs, IRS and intensified surveillance response or mass vaccination, for malaria control.

Use of plant volatiles

The physiological need of mosquitoes, both male and female, to obtain energy from sugar could be exploited and utilized to lure mosquitoes into traps baited with highly selective insecticides or entomopathogenic agents such as fungi and viruses. Anopheles control programs are already successfully implementing strategies that use attractive toxic sugar baits (ATSB) based on attractants from flowers and/or fruits to attract the mosquitoes. These ATSB's also include sugar to induce feeding, and an oral toxin to kill the mosquitoes. The technique has resulted in substantial reductions in the mosquito populations at the sites where it has been tested[121–123].

Aedes albopictus control programs have also had similar success with ATSB[108] based on guava mango nectars which have proven to be attractant in trapping male *Ae. aegypti* too[103]. There is also a potential to use several floral-based attractants, including acetophenone and phenylacetaldehyde that have shown to be attractive to *Ae. aegypti* in small scale experiments in traps[104, 107].

ATSBs dispersed in bait stations, in conjunction with bed nets, have also been evaluated with the idea that host-seeking mosquitoes will deplete their energy reserves trying to access the host and thus would then require a sugar meal to regain their energy reserves and imbibe the available ATSB solutions[124]. Mortality rates in such stations were observed to range from 41% to 48% against *An. arabiensis* and 36%–43% against *Cx. quinquefasciatus.* Other studies have even gone further and integrated bacteria or double-stranded RNA (dsRNA) into toxic sugar baits[125–126] against Aedine and Anopheline mosquitoes with success.

Apart from floral nectar odours, the knowledge of semiochemicals mediating mosquito-plant interaction has also been exploited in integrated vector management is *Culex quinquefasciatus* oviposition pheromone ((*5R*,*6S*)-acetoxy-5-hexadecanolide) which when combined with the insect growth regulator pyriproxifen resulted in increased oviposition accompanied by killing of the emerging larvae[127]. Also studies have shown that spraying of vegetations around water bodies with attractive toxic sugar baits can reduce mosquito populations by up to 98%[128–129].

It's important to note that apart from mosquito-plant interaction being utilized in luring mosquitoes into traps baited with highly selective insecticides or entomopathogenic agents such as fungi and viruses, phyto chemicals could be used as general toxicants against immature mosquitoes, repellents, larvicidal, ovicidal and oviposition deterrents, growth and reproduction inhibitors as well as attractants[6, 130–131].

CONCLUSION

Semiochemicals alone might not be sufficient as a control tool against mosquitoes, but their use can be maximized through integration with other existing mosquito vector control strategies which can provide a powerful tool that can help reduce and even eliminate vector populations.

Conflict interest: None

REFERENCES

1. World malaria report 2019. Available from: https://www.who.int/publications-detail-redirect/9789241565721 (Accessed on October 19, 2020)
2. Dengue and severe dengue. Available from: https://www.who.int/news-room/fact-sheets/detail/dengue-and-severe-dengue. (Accessed on October 19, 2020)

3. Kline D. Semiochemicals, traps/targets and mass trapping technology for mosquito management. *J Am Mosq Control Assoc* 2007; *23*: 241–51.
4. Pickett JA, Birkett MA, Dewhirst SY, Logan JG, Omolo MO, Torto B, *et al*. Chemical ecology of animal and human pathogen vectors in a changing global climate. *J Chem Ecol* 2010; *36*(1): 113–21.
5. Menger DJ, Otieno B, de Rijk M, Mukabana WR, van Loon JJ, Takken W. A push-pull system to reduce house entry of malaria mosquitoes. *Malar J* 2014; *13*: 119.
6. Menger DJ, Omusula P, Holdinga M, Homan T, Carreira AS, Vandendaele P, *et al.* Field Evaluation of a Push-Pull System to Reduce Malaria Transmission *PLOS ONE* 2015; *10*(4): e0123415.
7. Menger DJ, Omusula P, Wouters K, Oketch C, Carreira AS, Durka M, *et al*. Eave Screening and Push-Pull Tactics to Reduce House Entry by Vectors of Malaria. *Am J Trop Med Hyg* 2016; *94*(4): 868–78.
8. CDC Miniature Light Trap — The John W. Hock Company. Available from: https://www.johnwhock.com/products/mosquito-sandfly-traps/cdc-miniature-light-trap/ (Accessed on October 19, 2020)
9. Geier M, Rose A, Gunewald J, Jones O. New mosquito traps improve the monitoring of disease vectors. *Int Pest Contro* 2006 1; *48*: 124–6.
10. Smith CN, Smith N, Gouck HK, Weidhaas DE, Gilbert IH, Mayer MS, *et al*. L-lactic acid as a factor in the attraction of Aedes aegypti (Diptera: Culicidae) to human hosts. *Ann Entomol Soc Am* 1970; *63*(3): 760–70.
11. Eiras AE, Jepson PC. Responses of female Aedes aegypti (Diptera: Culicidae) to host odours and convection currents using an olfactometer bioassay. *Bull Entomol Res* 1994; *84*(2): 207–11.
12. Bernier UR, Kline DL, Posey KH, Booth MM, Yost RA, Barnard DR. Synergistic Attraction of Aedes aegypti (L.) to Binary Blends of L-Lactic Acid and Acetone, Dichloromethane, or Dimethyl Disulfide. *J Med Entomol* 2003; *40*(5): 653–6.
13. Bernier UR, Booth MM, Yost RA. Analysis of human skin emanations by gas chromatography/mass spectrometry. 1. Thermal desorption of attractants for the yellow fever mosquito (Aedes aegypti) from handled glass beads. *Anal Chem* 1999; *71*(1): 1–7.
14. Bernier U, Kline D, Barnard D, Schreck C, Yost R. Analysis of Human Skin Emanations by Gas Chromatography/Mass Spectrometry. 2. Identification of Volatile Compounds That Are Candidate Attractants for the Yellow Fever Mosquito (Aedes aegypti). *Anal Chem* 2000; *72*: 747–56.
15. Allan SA, Bernier UR, Kline DL. Laboratory evaluation of lactic acid on attraction of Culex spp. (Diptera: Culicidae). *J Vector Ecol* 2010; *35*(2): 318–24.
16. Braks M a. H, Meijerink J, Takken W. The response of the malaria mosquito, Anopheles gambiae, to two components of human sweat, ammonia and l-lactic acid, in an olfactometer. *Physiol Entomol* 2001; *26*(2): 142–8.
17. Costantini C, Birkett MA, Gibson G, Ziesmann J, Sagnon N, Mohammed HA, *et al*. Electroantennogram and behavioural responses of the malaria vector Anopheles gambiae to human-specific sweat components. *Med Vet Entomol* 2001; *15*(3): 259–66.
18. Qiu YT, Smallegange RC, Hoppe S, Loon JJAV, Bakker E-J, Takken W. Behavioural and electrophysiological responses of the malaria mosquito Anopheles gambiae Giles sensu stricto (Diptera: Culicidae) to human skin emanations. *Med Vet Entomol* 2004; *18*(4): 429–38.
19. Tchouassi DP, Sang R, Sole CL, Bastos ADS, Teal PEA, Borgemeister C, *et al*. Common Host-Derived Chemicals Increase Catches of Disease-Transmitting Mosquitoes and Can Improve Early Warning Systems for Rift Valley Fever Virus. *PLoS Negl Trop Dis* 2013 ;*7*(1).
20. Owino EA, Sang R, Sole CL, Pirk C, Mbogo C, Torto B. An improved odor bait for monitoring populations of Aedes aegypti-vectors of dengue and chikungunya viruses in Kenya. *Parasit Vectors* 2015; *8* :253.
21. Okumu FO, Killeen GF, Ogoma S, Biswaro L, Smallegange RC, Mbeyela E, *et al*. Development and Field Evaluation of a Synthetic Mosquito Lure That Is More Attractive than Humans. *PLOS ONE* 2010; *5*(1): e8951.
22. Mukabana WR, Mweresa CK, Otieno B, Omusula P, Smallegange RC, van Loon JJA, *et al.* A Novel Synthetic Odorant Blend for Trapping of Malaria and Other African Mosquito Species. *J Chem Ecol* 2012; *38*(3): 235–44.
23. Mweresa CK, Mukabana WR, Omusula P, Otieno B, Van Loon JJA, Takken W. Enhancing Attraction of African Malaria Vectors to a Synthetic Odor Blend. *J Chem Ecol* 2016; *42*(6): 508–16.
24. Smallegange RC, Knols BGJ, Takken W. Effectiveness of Synthetic Versus Natural Human Volatiles as Attractants for Anopheles gambiae (Diptera: Culicidae) Sensu Stricto. *J Med Entomol* 2010; *47*(3): 338–44.
25. Homan T, Hiscox A, Mweresa CK, Masiga D, Mukabana WR, Oria P, *et al.* The effect of mass mosquito trapping on malaria transmission and disease burden (SolarMal): a stepped-wedge cluster-randomised trial. *The Lancet* 2016; *388*(10050): 1193–201.
26. Foster WA. Mosquito sugar feeding and reproductive energetics. *Annu Rev Entomol* 1995; *40*: 443–74.
27. Burgess L. Probing Behaviour of Ædes ægypti (L.) in Response to Heat and Moisture. *Nature* 1959; *184*(4703): 1968–9.
28. Gibson G, Torr SJ. Visual and olfactory responses of haematophagous Diptera to host stimuli. *Med Vet Entomol* 1999; *13*(1): 2–23.
29. Kröber T, Kessler S, Frei J, Bourquin M, Guerin PM. An in vitro assay for testing mosquito repellents employing a warm body and carbon dioxide as a behavioral activator. *J Am Mosq Control Assoc* 2010; *26*(4): 381–6.
30. McMeniman CJ, Corfas RA, Matthews BJ, Ritchie SA, Vosshall LB. Multimodal Integration of Carbon Dioxide and Other Sensory Cues Drives Mosquito Attraction to Humans. *Cell* 2014; *156*(5): 1060–71.
31. Gillies MT. The role of carbon dioxide in host-finding by mosquitoes (Diptera: Culicidae): a review. Bull Entomol Res 1980; *70*(4): 525–32.
32. Acree F, Turner RB, Gouck HK, Beroza M, Smith N. L-Lactic acid: a mosquito attractant isolated from humans. *Science* 1968; *161*(3848): 1346–7.
33. Schreck C, Kline D, Carlson D. Mosquito attraction to substances from the skin of different humans. *J Am Mosq Control Assoc* 1990; *6*: 406–10.
34. Steib B. The Effect of Lactic Acid on Odour-Related Host Preference of Yellow Fever Mosquitoes. *Chem Senses* 2001; *26*: 523–8.
35. Dekker T, Steib B, Cardé RT, Geier M. L-lactic acid: a human-signifying host cue for the anthropophilic mosquito Anopheles gambiae. *Med Vet Entomol* 2002; *16*(1): 91–8.
36. Smallegange RC, Qiu YT, van Loon JJA, Takken W. Synergism between ammonia, lactic acid and carboxylic acids as kairo-

mones in the host-seeking behaviour of the malaria mosquito Anopheles gambiae sensu stricto (Diptera: Culicidae). *Chem Senses* 2005; *30*(2):145–52.
37. Bernier UR, Kline DL, Schreck CE, Yost RA, Barnard DR. Chemical analysis of human skin emanations: comparison of volatiles from humans that differ in attraction of Aedes aegypti (Diptera: Culicidae). *J Am Mosq Control Assoc* 2002; *18*(3):186–95.
38. Haze S, Gozu Y, Nakamura S, Kohno Y, Sawano K, Ohta H, *et al*. 2-Nonenal Newly Found in Human Body Odor Tends to Increase with Aging. *J Invest Dermatol* 2001; *116*(4): 520–4.
39. Gallagher M, Wysocki C, Leyden, JJ, Spielman A, AI, *et al*. Analyses of Volatile Organic Compounds from Human Skin. *Br J Dermatol* 2008; *159*: 780–91.
40. Curran A, Rabin S, Prada-Tiedemann P, Furton K. Comparison of the Volatile Organic Compounds Present in Human Odor Using Spme-GC/MS. *J Chem Ecol* 2005; *31*:1607–19.
41. Curran A, Rabin S, Furton K. Analysis of the Uniqueness and Persistence of Human Scent. *Forensic Sci Commun* 2005; *7*.
42. Curran AM, Ramirez CF, Schoon AA, Furton KG. The frequency of occurrence and discriminatory power of compounds found in human scent across a population determined by SPME-GC/MS. *J Chromatogr B Analyt Technol Biomed Life Sci* 2007; *846*(1–2): 86–97.
43. Rudolfs W. Chemotropism of Mosquitoes. Available from: https://www.cabdirect.org/cabdirect/abstract/19221000556 (Accessed on October 19, 2020)
44. Healy TP, Copland MJ. Activation of Anopheles gambiae mosquitoes by carbon dioxide and human breath. *Med Vet Entomol* 1995; *9*(3): 331–6.
45. Lacey E, Cardé R. Activation, orientation and landing of female Culex quinquefasciatus in response to carbon dioxide and odour from human feet: 3-D flight analysis in a wind tunnel. *Med Vet Entomol* 2011; *25*: 94–103.
46. Dekker T, Geier M, Cardé R. Carbon dioxide instantly sensitizes female yellow fever mosquitoes to human skin odour. *J Exp Biol* 2005; *208*: 2963–72.
47. Dekker T, Cardé R. Moment-to-moment flight manoeuvres of the female yellow fever mosquito (Aedes aegypti L.) in response to plumes of carbon dioxide and human skin odour. *J Exp Biol* 2011; *214*: 3480–94.
48. Costantini C, Gibson G, Sagnon N, Della Torre A, Brady J, Coluzzi M. Mosquito responses to carbon dioxide in a west African Sudan savanna village. *Med Vet Entomol* 1996; *10*(3): 220–7.
49. Jerry DCT, Mohammed T, Mohammed A. Yeast-generated CO2: A convenient source of carbon dioxide for mosquito trapping using the BG-Sentinel® traps. *Asian Pac J Trop Biomed* 2017; *7*(10): 896–900.
50. Becker N, Zgomba M, Petric D, Ludwig M. Comparison of carbon dioxide, octenol and a host-odour as mosquito attractants in the Upper Rhine Valley, Germany. *Med Vet Entomol* 1995; 9(4): 377–80.
51. Nyasembe VO, Tchouassi DP, Kirwa HK, Foster WA, Teal PEA, Borgemeister C, *et al*. Development and Assessment of Plant-Based Synthetic Odor Baits for Surveillance and Control of Malaria Vectors. *PLoS ONE* 2014; *9*(2).
52. Mweresa CK, Omusula P, Otieno B, van Loon JJ, Takken W, Mukabana WR. Molasses as a source of carbon dioxide for attracting the malaria mosquitoes Anopheles gambiae and Anopheles funestus. *Malar J* 2014; *13*(1): 160.
53. Mboera LEG, Knols BGJ, Braks M a. H, Takken W. Comparison of carbon dioxide-baited trapping systems for sampling outdoor mosquito populations in Tanzania. *Med Vet Entomol* 2000; *14*(3): 257–63.
54. Russell RC. The relative attractiveness of carbon dioxide and octenol in CDC- and EVS-type light traps for sampling the mosquitoes Aedes aegypti (L.), Aedes polynesiensis Marks, and Culex quinquefasciatus say in Moorea, French Polynesia. *J Vector Ecol J Soc Vector Ecol* 2004; *29*(2): 309–14.
55. Muturi EJ, Mwangangi J, Shililu J, Muriu S, Jacob B, Mbogo CM, *et al*. Evaluation of Four Sampling Techniques for Surveillance of Culex quinquefasciatus (Diptera: Culicidae) and Other Mosquitoes in African Rice Agroecosystems. *J Med Entomol* 2007; *44*(3): 503–8.
56. Pombi M, Jacobs F, Verhulst NO, Caputo B, della Torre A, Takken W. Field evaluation of a novel synthetic odour blend and of the synergistic role of carbon dioxide for sampling host-seeking Aedes albopictus adults in Rome, Italy. Available from: *https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4271472/*. (Accessed on October 19, 2020)
57. Zhang H-L, Zhang Y-Z, Yang W-H, Feng Y, Nasci RS, Yang J, *et al*. Mosquitoes of Western Yunnan Province, China: Seasonal Abundance, Diversity, and Arbovirus Associations. *PLoS ONE* 2013; *8*(10).
58. Canyon DV, Hii JL. Efficacy of carbon dioxide, 1-octen-3-ol, and lactic acid in modified Fay-Prince traps as compared to man-landing catch of Aedes aegypti. *J Am Mosq Control Assoc* 1997; *13*(1): 66–70.
59. Sukumaran D. A review on use of attractants and traps for host seeking Aedes aegypti mosquitoes. 2016 ; *7*: 207–14.
60. Smallegange RC, Schmied WH, van Roey KJ, Verhulst NO, Spitzen J, Mukabana WR, *et al.* Sugar-fermenting yeast as an organic source of carbon dioxide to attract the malaria mosquito Anopheles gambiae. *Malar J* 2010; *9*(1): 292.
61. Eiras AE, Jepson PC. Host location by Aedes aegypti (Diptera: Culicidae): a wind tunnel study of chemical cues. *Bull Entomol Res* 1991; *81*(2): 151–60.
62. Vale GA. Field responses of tsetse flies (Diptera: Glossinidae) to odours of men, lactic acid and carbon dioxide. *Bull Entomol Res* 1979; *69*(3): 459–67.
63. Geier M, Bosch OJ, Boeckh J. Ammonia as an Attractive Component of Host Odour for the Yellow Fever Mosquito, Aedes aegypti. *Chem Senses* 1999; *24*(6): 647–53.
64. Bosch OJ, Geier M, Boeckh J. Contribution of Fatty Acids to Olfactory Host Finding of Female Aedes aegypti. *Chem Senses* 2000 ; *25*(3): 323–30.
65. Stryker RG, Young WW. Effectiveness of carbon dioxide and L(+) lactic acid in mosquito light traps with and without light. *Mosq News* 1970; *30*(3).
66. Kline DL, Takken W, Wood JR, Carlson DA. Field studies on the potential of butanone, carbon dioxide, honey extract, l-octen-3-ol, L-lactic acid and phenols as attractants for mosquitoes*. *Med Vet Entomol* 1990; *4*(4): 383–91.
67. Guidobaldi F, Guerenstein PG. Evaluation of a CO2-free commercial mosquito attractant to capture triatomines in the laboratory. *J Vector Ecol* 2013; *38*(2): 245–50.
68. Hoel DF, Kline DL, Allan SA, Grant A. Evaluation of carbon dioxide, 1-octen-3-ol, and lactic acid as baits in Mosquito Magnet Pro traps for Aedes albopictus in north central Florida. *J Am Mosq Control Assoc* 2007; *23*(1): 11–7.
69. Williams CR, Bergbauer R, Geier M, Kline DL, Bernier U, Russell R, *et al.* Laboratory and field assessment of some kairomone blends for host-seeking Aedes aegypti. *J Am Mosq Control As-*

soc 2006; *22*: 641–7.

70. Busula AO, Takken W, Loy DE, Hahn BH, Mukabana WR, Verhulst NO. Mosquito host preferences affect their response to synthetic and natural odour blends. *Malar J* 2015; *14*: 133.
71. Omrani S-M, Vatandoost H, Oshaghi M, Shokri F, Yaghoobi-Ershadi M, Rassi Y, *et al*. Differential Responses of Anopheles stephensi (Diptera: Culicidae) to Skin Emanations of a Man, a Cow, and a Guinea Pig in the Olfactometer. *Iran J Arthropod-Borne Dis* 2010; *4*(1): 1–16.
72. Mohr RM, Mullens BA, Gerry AC. Evaluation of ammonia, human sweat, and bovine blood as attractants for the female canyon fly, Fannia conspicua (Diptera: Muscidae), in southern California. *J Vector Ecol* 2011; *36*(1): 55–8.
73. Verhulst NO, Mbadi PA, Kiss GB, Mukabana WR, van Loon JJ, Takken W, *et al*. Improvement of a synthetic lure for Anopheles gambiae using compounds produced by human skin microbiota. *Malar J* 2011 Feb 8; *10*: 28.
74. Zohdy S, Derfus K, Andrianjafy MT, Wright PC, Gillespie TR. Field evaluation of synthetic lure (3-methyl-1-butanol) when compared to non odor-baited control in capturing Anopheles mosquitoes in varying land-use sites in Madagascar. *Parasit Vectors* 2015; *8*.
75. Kline DL. Olfactory attractants for mosquito surveillance and control: 1-octen-3-ol. J Am *Mosq Control Assoc*. 1994 ;*10*(2 Pt 2): 280–7.
76. Njiru BN, Mukabana WR, Takken W, Knols BG. Trapping of the malaria vector Anopheles gambiae with odour-baited MM-X traps in semi-field conditions in western Kenya. *Malar J* 2006; *5*: 39.
77. Merdic enrih@biologija. unios. hr, Krčmar S, Bogojevic M, Jelicic Marinkovic Z. Response of mosquitoes to different synthetic and natural olfactory attractants (Diptera : Culicidae). *Entomol Gen* 2007; *30*: 253–61.
78. Laporta GZ, Sallum MAM. Effect of CO2 and 1-octen-3-ol attractants for estimating species richness and the abundance of diurnal mosquitoes in the southeastern Atlantic forest, Brazil. *Mem Inst Oswaldo Cruz* 2011; *106*(3): 279–84.
79. Magalhães-Junior JT, Barrouin-Melo SM, Corrêa AG, da Rocha Silva FB, Machado VE, Govone JS, et al. A laboratory evaluation of alcohols as attractants for the sandfly Lutzomyia longipalpis (Diptera:Psychodidae). *Parasit Vectors* 2014; *7*: 60.
80. Vale GA. Development of baits for tsetse flies (Diptera: Glossinidae) in Zimbabwe. *J Med Entomol* 1993; *30*(5): 831–42.
81. Hall DR, Beevor PS, Cork A, Nesbitt BF, Vale GA. 1-Octen-3-ol. A potent olfactory stimulant and attractant for tsetse isolated from cattle odours. *Int J Trop Insect Sci* 1984; *5*(5): 335–9.
82. Cilek JE, Ikediobi CO, Hallmon CF, Johnson R, Onyeozili EN, Farah SM, *et al*. Semi-field evaluation of several novel alkenol analogs of 1-octen-3-ol as attractants to adult Aedes albopictus and Culex quinquefasciatus. *J Am Mosq Control Assoc* 2011; *27*(3): 256–62.
83. Logan JG, Birkett MA, Clark SJ, Powers S, Seal NJ, Wadhams LJ, *et al.* Identification of Human-Derived Volatile Chemicals that Interfere with Attraction of Aedes aegypti Mosquitoes. *J Chem Ecol* 2008; *34*(3): 308.
84. Robinson A, Busula AO, Voets MA, Beshir KB, Caulfield JC, Powers SJ, *et al*. Plasmodium-associated changes in human odor attract mosquitoes. *Proc Natl Acad Sci* 2018; *115*(18): E4209–18.
85. Leal HM, Hwang JK, Tan K, Leal WS. Attraction of Culex mosquitoes to aldehydes from human emanations. *Sci Rep* 2017; *7*(1): 17965.
86. Ghaninia M, Larsson M, Hansson BS, Ignell R. Natural odor ligands for olfactory receptor neurons of the female mosquito Aedes aegypti: use of gas chromatography-linked single sensillum recordings. *J Exp Biol* 2008; *211*(Pt 18): 3020–7.
87. Ye Z, Liu F, Liu N. Olfactory Responses of Southern House Mosquito, Culex quinquefasciatus , to Human Odorants. *Chem Senses* 2016; *41*(5): 441–7.
88. Syed Z, Leal WS. Acute olfactory response of Culex mosquitoes to a human- and bird-derived attractant. *Proc Natl Acad Sci* 2009; *106*(44): 18803–8.
89. Cooperband MF, McElfresh JS, Millar JG, Cardé RT. Attraction of female Culex quinquefasciatus Say (Diptera: Culicidae) to odors from chicken feces. *J Insect Physiol* 2008; *54*(7): 1184–92.
90. Stoddart. Scented Ape: Biology of Human Odour. 1st Edition. Cambridge: Cambridge University Press; 2008. 300 p.
91. Roessler HP. Versuche zur Geruchlichen Anlockung Weiblicher Stechmücken (Aëdes Aegypti L., Culicidae). *Z Für Vgl Physiol* 1961; *44*(2): 184–231.
92. Cork A, Park KC. Identification of electrophysiologically-active compounds for the malaria mosquito, Anopheles gambiae, in human sweat extracts. *Med Vet Entomol* 1996; *10*(3): 269–76.
93. Skinner WA, Tong H, Maibach H, Khan AA, Pearson T. Repellency of Skin-Surface Lipids of Humans to Mosquitoes. *Science* 1965; *149*(3681): 305–6.
94. Skinner WA, Tong HC, Pearson TR, Maibach HI. Repellency of human skin-surface lipid hydrocarbons to the yellow-fever mosquito. *J Econ Entomol* 1967; *60*(4): 927–9.
95. Kline DL, Bernier UR, Hogsette JA. Efficacy of Three Attractant Blends Tested in Combination with Carbon Dioxide Against Natural Populations of Mosquitoes and Biting Flies at the Lower Suwannee Wildlife Refuge. *J Am Mosq Control Assoc* 2012 Jun; *28*(2): 123–7.
96. Hull CD, Cribb BW. Olfaction in the Queensland Fruit Fly, Bactrocera tryoni. I: Identification of Olfactory Receptor Neuron Types Responding to Environmental Odors. *J Chem Ecol* 2001; *27*(5): 871–87.
97. Turner SL, Li N, Guda T, Githure J, Cardé RT, Ray A. Ultra-prolonged activation of CO 2 -sensing neurons disorients mosquitoes. *Nature* 2011; *474*(7349): 87–91.
98. Van Handel E. The obese mosquito. *J Physiol* 1965; *181*(3): 478–86.
99. Otienoburu PE, Ebrahimi B, Phelan PL, Foster WA. Analysis and Optimization of a Synthetic Milkweed Floral Attractant for Mosquitoes. *J Chem Ecol* 2012 Jul; *38*(7): 873–81.
100. Foster WA, Hancock RG. Nectar-related olfactory and visual attractants for mosquitoes. *J Am Mosq Control Assoc* 1994; *10*(2 Pt 2): 288–96.
101. Reisen WK, Meyer RP, Milby MM. Patterns of Fructose Feeding by Culex Tarsalis (Diptera: Culicidae). *J Med Entomol* 1986; *23*(4): 366–73.
102. Nyasembe VO, Teal PE, Mukabana WR, Tumlinson JH, Torto B. Behavioural response of the malaria vector Anopheles gambiae to host plant volatiles and synthetic blends. *Parasit Vectors* 2012; *5*(1): 234.
103. Fikrig K, Johnson BJ, Fish D, Ritchie SA. Assessment of synthetic floral-based attractants and sugar baits to capture male and female Aedes aegypti (Diptera: Culicidae). *Parasit Vectors* 2017; *10*.
104. Von Oppen SM, Masuh HM, Licastro SM, Zerba EN, Gonzalez Audino PA. A floral-derived attractant for Aedes aegypti mosquitoes. Available from: *http://ri.conicet.gov.ar/han-*

dle/11336/38689 (Accessed on October 19, 2020)

105. Jacob JW, Tchouassi DP, Lagat ZO, Mathenge EM, Mweresa CK, Torto B. Independent and interactive effect of plant- and mammalian- based odors on the response of the malaria vector, Anopheles gambiae. *Acta Trop* 2018; *185*: 98–106.
106. Müller GC, Beier JC, Traore SF, Toure MB, Traore MM, Bah S, *et al*. Field experiments of Anopheles gambiae attraction to local fruits/seedpods and flowering plants in Mali to optimize strategies for malaria vector control in Africa using attractive toxic sugar bait methods. *Malar J* 2010; *9*: 262.
107. Jhumur US, Dötterl S, Jürgens A. Electrophysiological and behavioural responses of mosquitoes to volatiles of Silene otites (Caryophyllaceae). *Arthropod-Plant Interact* 2007; *1*(4): 245.
108. Revay EE, Müller GC, Qualls WA, Kline DL, Naranjo DP, Arheart KL, *et al*. Control of Aedes albopictus with attractive toxic sugar baits (ATSB) and potential impact on non-target organisms in St. Augustine, Florida. *Parasitol Res* 2014; *113*(1): 73–9.
109. Müller GC, Xue R-D, Schlein Y. Differential attraction of Aedes albopictus in the field to flowers, fruits and honeydew. *Acta Trop* 2011; *118*(1): 45–9.
110. Honda K, Ômura H, Hayashi N. Identification of Floral Volatiles From Ligustrum japonicum that Stimulate Flower-Visiting by Cabbage Butterfly, Pieris rapae. *J Chem Ecol* 1998; *24*(12): 2167–80.
111. Bentley MD, McDaniel IN, Davis EE. Studies of 4-Methylcyclohexanol: an Aedes Triseriatus (Diptera: Culicidae) Oviposition Attractant. *J Med Entomol* 1982; *19*(5): 589–92.
112. Bowen MF. Terpene-sensitive receptors in female Culex pipiens mosquitoes: Electrophysiology and behaviour. *J Insect Physiol* 1992; *38*(10): 759–64.
113. Jhumur US, Dötterl S, Jürgens A. Floral odors of Silene otites: their variability and attractiveness to mosquitoes. *J Chem Ecol* 2008; *34*(1): 14–25.
114. Dötterl S, Burkhardt D, Weissbecker B, Jürgens A, Schütz S, Mosandl A. Linalool and lilac aldehyde/alcohol in flower scents. Electrophysiological detection of lilac aldehyde stereoisomers by a moth. *J Chromatogr A* 2006; *1113*(1–2): 231–8.
115. Horstick O, Runge-Ranzinger S, Nathan MB, Kroeger A. Dengue vector-control services: how do they work? A systematic literature review and country case studies. *Trans R Soc Trop Med Hyg* 2010; *104*(6): 379–86.
116. Fonseca-Gonzalez I, Quiñones M, Lenhart A, Brogdon W. Insecticide resistance status of Aedes aegypti (L.) from Colombia. *Pest Manag Sci* 2011; *67*: 430–7.
117. Polson KA, Brogdon WG, Rawlins SC, Chadee DD. Characterization of insecticide resistance in Trinidadian strains of Aedes aegypti mosquitoes. *Acta Trop* 2011; *117*(1): 31–8.
118. Cook S, Khan Z, Pickett J. The Use of Push-Pull Strategies in Integrated Pest Management. *Annu Rev Entomol* 2007 Feb 1; *52*: 375–400.
119. Obermayr U, Ruther J, Bernier UR, Rose A, Geier M. Evaluation of a Push-Pull Approach for Aedes aegypti (L.) Using a Novel Dispensing System for Spatial Repellents in the Laboratory and in a Semi-Field Environment. *PloS One* 2015; *10*(6): e0129878.
120. Lindsay SW, Jawara M, Paine K, Pinder M, Walraven GEL, Emerson PM. Changes in house design reduce exposure to malaria mosquitoes. *Trop Med Int Health TM IH* 2003; *8*(6): 512–7.
121. Müller GC, Kravchenko VD, Schlein Y. Decline of Anopheles sergentii and Aedes caspius populations following presentation of attractive toxic (spinosad) sugar bait stations in an oasis. *J Am Mosq Control Assoc* 2008; *24*(1): 147–9.
122. Müller GC, Beier JC, Traore SF, Toure MB, Traore MM, Bah S, *et al*. Successful field trial of attractive toxic sugar bait (ATSB) plant-spraying methods against malaria vectors in the Anopheles gambiae complex in Mali, West Africa. *Malar J* 2010; *9*(1): 210.
123. Revay EE, Schlein Y, Tsabari O, Kravchenko V, Qualls W, De-Xue R, *et al*. Formulation of attractive toxic sugar bait (ATSB) with safe EPA-exempt substance significantly diminishes the Anopheles sergentii population in a desert oasis. *Acta Trop* 2015; *150*: 29–34.
124. Stewart ZP, Oxborough RM, Tungu PK, Kirby MJ, Rowland MW, Irish SR. Indoor application of attractive toxic sugar bait (ATSB) in combination with mosquito nets for control of pyrethroid-resistant mosquitoes. *PloS One* 2013; *8*(12): e84168.
125. Lindh JM, Terenius O, Eriksson-Gonzales K, Knols BGJ, Faye I. Re-introducing bacteria in mosquitoes--a method for determination of mosquito feeding preferences based on coloured sugar solutions. *Acta Trop* 2006; *99*(2–3): 173–83.
126. Shin E, Park C, Ahn Y-J, Lee D-K, Chang K-S. Insecticidal and repellent activities of insecticide-sucrose solutions to Culex pipiens molestus (Diptera: Culicidae) under laboratory and field conditions. *Pest Manag Sci* 2011; *67*(6): 665–71.
127. Mboera LE, Takken W, Mdira KY, Pickett JA. Sampling gravid Culex quinquefasciatus (Diptera: Culicidae) in Tanzania with traps baited with synthetic oviposition pheromone and grass infusions. *J Med Entomol* 2000; *37*(1): 172–6.
128. Schlein Y, Müller GC. An Approach to Mosquito Control: Using the Dominant Attraction of Flowering Tamarix jordanis Trees Against Culex pipiens. *J Med Entomol* 2008; *45*(3): 384–90.
129. Beier JC, Müller GC, Gu W, Arheart KL, Schlein Y. Attractive toxic sugar bait (ATSB) methods decimate populations of Anopheles malaria vectors in arid environments regardless of the local availability of favoured sugar-source blossoms. *Malar J* 2012; *11*: 31.
130. Rajkumar S, Jebanesan A. Oviposition deterrent and skin repellent activities of Solanum trilobatum leaf extract against the malarial vector Anopheles stephensi. *J Insect Sci Online* 2005; *5*: 15.
131. Pushpanathan T, Jebanesan A, Govindarajan M. Larvicidal, ovicidal and repellent activities of Cymbopogan citratus Stapf (Graminae) essential oil against the filarial mosquito Culex quinquefasciatus (Say) (Diptera : Culicidae). *Trop Biomed* 2006; *23*(2): 208–12.

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