ANNUAL REVIEWS

Annual Review of Entomology

Chemical Ecology and Management of Dengue Vectors

Baldwyn Torto* and David P. Tchouassi*

International Centre of Insect Physiology and Ecology, Nairobi, Kenya;
email: btorto@icipe.org, dtchouassi@icipe.org

Annu. Rev. Entomol. 2024. 69:159–82

First published as a Review in Advance on
August 25, 2023

The *Annual Review of Entomology* is online at
ento.annualreviews.org

https://doi.org/10.1146/annurev-ento-020123-015755

*Corresponding authors

Keywords

semiochemicals, behavior, dengue, arbovirus surveillance, arbovirus control, *Aedes aegypti*, *Aedes albopictus*

Abstract

Dengue, caused by the dengue virus, is the most widespread arboviral infectious disease of public health significance globally. This review explores the communicative function of olfactory cues that mediate host-seeking, egg-laying, plant-feeding, and mating behaviors in *Aedes aegypti* and *Aedes albopictus*, two mosquito vectors that drive dengue virus transmission. *Aedes aegypti* has adapted to live in close association with humans, preferentially feeding on them and laying eggs in human-fabricated water containers and natural habitats. In contrast, *Ae. albopictus* is considered opportunistic in its feeding habits and tends to inhabit more vegetative areas. Additionally, the ability of both mosquito species to locate suitable host plants for sugars and find mates for reproduction contributes to their survival. Advances in chemical ecology, functional genomics, and behavioral analyses have improved our understanding of the underlying neural mechanisms and reveal novel and specific olfactory semiochemicals that these species use to locate and discriminate among resources in their environment. Physiological status; learning; and host- and habitat-associated factors, including microbial infection and abundance, shape olfactory responses of these vectors. Some of these semiochemicals can be integrated into the toolbox for dengue surveillance and control.

INTRODUCTION

Dengue is the most widespread arboviral infectious disease afflicting mankind globally, resulting in significant morbidity, mortality, and economic impact in tropical and subtropical regions (141). Approximately half of the world's population is at risk of dengue, with an estimated 100–400 million annual infections (141). The disease is caused by dengue virus, which exists as four distinct serotypes (DENV 1–4). Dengue infection in humans may present as a mild or acute flu-like illness (>80%), with only a minor proportion (5–10%) of cases developing severe dengue characterized by dengue hemorrhagic fever and dengue shock syndrome (141).

The alarming rise and expanding epidemiology of the disease have been facilitated largely by fast-growing human populations, rapid urbanization without adequate sanitary provision, deforestation, increased travel, and climate change (54, 111). As such, the virus has spread and established in new geographic locations where the competent mosquito vectors *Aedes aegypti* and *Aedes albopictus* contribute to its circulation among a large population of immunologically naive human hosts. Notably, these mosquito species also vector other arboviruses, such as the chikungunya, Zika, and yellow fever viruses (111).

To date, only one effective and safe vaccine (CYD-TDV) has been developed to protect humans against the virus. However, it is recommended for use in seropositive individuals only, that is, those with a history of dengue virus infection, and approved for use in only a handful of countries (42, 141). This implies that vaccine rollout in the general population requires prevaccination screening, making it an unsustainable strategy. With no specific antiviral therapy available, vector control remains the mainstay tool for dengue prevention (141).

The growing health risk of dengue virus infection has increased the need to investigate the ecology of the virus vectors (**Figure 1**) to inform development of surveillance and control strategies. For instance, *Ae. aegypti* lives in close association with humans, which is an adaptation that has aided its survival and vectoring potential, fostered through repetitive cycles of human blood feeding and oviposition close to human dwellings (99, 123). *Aedes albopictus* is considered opportunistic in its feeding habits and tends to inhabit more vegetative rural and suburban areas. In most places, *Ae. aegypti* continues to be the main dengue vector, but this varies with geography; for example, in temperate areas of Europe, *Ae. albopictus* is the primary vector (51). Furthermore, recent studies have demonstrated the importance of plant feeding in these vectors, which was previously unappreciated, especially in the highly anthropophilic *Ae. aegypti* (123).

In this article, we review the fundamental differences in the biology and ecology of the two competent dengue virus vectors, *Ae. aegypti* and *Ae. albopictus*, and how these differences have shaped their chemical ecology and relative contributions to virus transmission risk and spread of dengue. We focus on the contributions of olfaction to specific behaviors of these two dengue vectors: host seeking for a blood meal from a vertebrate, plant feeding, mating, and oviposition. We discuss other literature detailing the contributions of olfaction that underlie these behaviors (for reviews, see 11, 82, 140), albeit minimally described in *Ae. albopictus*; however, we emphasize knowledge gaps related to the underlying genetic mechanisms modulating these behaviors. We include examples from sub-Saharan Africa (SSA) that are often underrepresented in the literature. Additionally, we present ideas for developing practical semiochemical-based tools for monitoring and control of dengue vectors.

NATURAL HISTORY AND BIOLOGY OF *AEDES AEGYPTI* AND *AEDES ALBOPICTUS*

Aedes aegypti (Linnaeus), commonly known as the yellow fever mosquito, is native to Africa. Its spread into tropical areas and, now, the subtropical and temperate regions of the world is thought

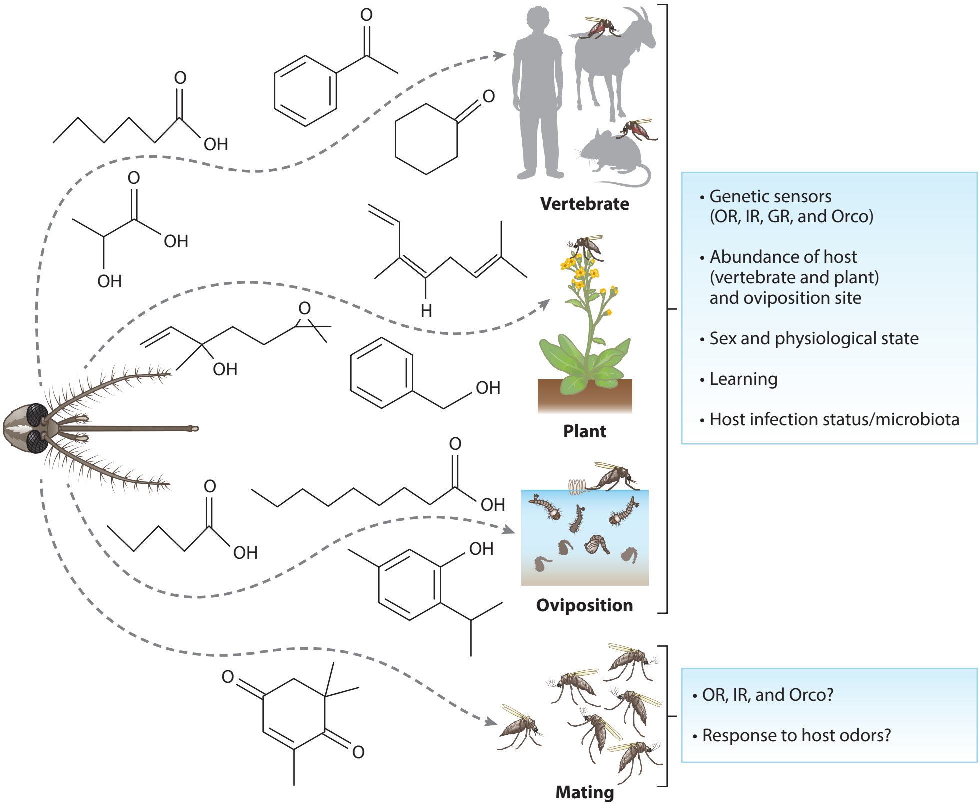

Figure 1

A representation of the key behaviors mediated by semiochemicals and the factors influencing their response. Question marks indicate roles in specific behaviors not yet defined. Abbreviations: GR, gustatory receptor; IR, ionotrophic receptor; OR, olfactory receptor; Orco, olfactory receptor coreceptor.

to have occurred in the past five centuries (49), primarily through its eggs, which are known to withstand desiccation (40, 119). Furthermore, the spread outside of Africa was accompanied by unique adaptations and ecogenetic divergence resulting in two forms or subspecies—the domestic *Ae. aegypti aegypti* (Aaa) and sylvatic *Ae. aegypti formosus* (Aaf). Aaa represents the invasive ecotype outside of Africa, with the ancestral Aaf found throughout most of SSA (75, 108). Aaa has adapted to breed in human-fabricated water containers and prefers to bite humans (i.e., it is a human specialist); these traits contribute to its role as an efficient arbovirus vector. In contrast, Aaf breeds in both natural and human habitats and feeds on diverse vertebrate hosts (75, 108). In East Africa, both forms co-occur in certain ecologies, as has been described in coastal Kenya (75, 108). Genetic methods are required to discriminate between the two subspecies (49, 123). The behavioral and ecological differences between these two forms are believed to impact their transmission of dengue virus.

The Asian tiger mosquito, *Ae. albopictus* (Skuse), originated in the forests of Southeast Asia (75), where it breeds in tree holes and other natural reservoirs. In recent years, it has become invasive in certain areas of Africa, Europe, and the Americas. As in *Ae. aegypti*, the primary route for its invasion is the trade in tires (51). Studies have shown that eggs of this mosquito species can also survive periods of dormancy. Compared to *Ae. aegypti*, *Ae. albopictus* exhibits a more plastic feeding habit on humans and domestic animals and tends to inhabit more vegetative rural and suburban areas (93). In contrast, *Ae. aegypti* prefers urban landscapes. Additionally, whereas *Ae. aegypti* thrives in the tropics and subtropics, *Ae. albopictus* adapts better to temperate climates and tends to displace *Ae. aegypti* in certain ecologies; however, co-occurrence is common, albeit in segregated habitats (105, 116).

AEDES AEGYPTI AND *AEDES ALBOPICTUS* VECTORIAL ATTRIBUTES AND INFLUENCE ON DENGUE

Dengue is an urban and semiurban disease (2, 141). *Aedes aegypti* thrives in both environments and is considered the primary vector of the dengue virus. In contrast, *Ae. albopictus* is less urbanized and considered a secondary vector of the virus. Blood meal analysis shows that *Ae. aegypti* consumes multiple partial blood meals, mainly from humans, during a single gonotrophic cycle (56). As such, this behavioral trait may allow it to sustain virus transmission and contribute to more explosive outbreaks, in contrast to the mild outcome most commonly known for *Ae. albopictus* (51). Nonetheless, frequent isolations of dengue viruses in wild specimens (51) indicate the susceptibility of both mosquito species to the dengue virus. However, in infection assays, *Ae. aegypti* may transmit the virus at higher rates than *Ae. albopictus* (63).

Blood meal analysis of wild *Ae. albopictus* specimens recorded human feeding rates exceeding 95% (63, 97). Since *Ae. albopictus* is rapidly expanding its geographic range, it could potentially replace *Ae. aegypti* in some of its established areas (51), and its importance in sustaining local dengue and other arboviral disease outbreaks worldwide could increase. *Aedes albopictus* is the driver of dengue outbreaks in temperate areas such as in Europe (51) and similar epidemics in *Ae. aegypti*–free regions and countries, including Hawaii and Mauritius. Its unique ecological flexibility has allowed it to act as a bridge vector to aid the movement of arboviruses across a wide geographic expanse (2).

Aedes albopictus has been predicted to maintain a foothold in Africa since its first detection in Nigeria in 1991. Since then, it has been implicated in large dengue outbreaks in urban areas of West and Central Africa (70) and, more recently, in Sudan (3).

For most of SSA, dengue dynamics are intimately linked to *Ae. aegypti* (2, 108, 111). However, behavioral divergence among the two subspecies (Aaa and Aaf), that is, divergence in blood-feeding preferences and vector competence, should be considered when designing interventions, including those that are semiochemical based.

HOST SEEKING FOR BLOOD AND ASSOCIATED INFOCHEMICALS

Host seeking in insects is comprised of a sequence of behavioral events, including activation, orientation or attraction, landing, and probing on the host (101). These behavioral events are triggered by cues that can be visual, tactile, acoustic, chemical, or a combination of these. Olfaction plays an important role in the host-seeking process, and insects detect odors via a variety of odorant receptors (ORs) expressed in olfactory sensory neurons (OSNs). The advances made over many decades in the development of more sensitive tools to collect and analyze volatiles and, more recently, computing power, statistical software and machine learning techniques, laboratory and field assays, and molecular and genetic studies have all helped to better understand the roles of olfactory semiochemicals in the host-seeking processes of *Ae. aegypti* and *Ae. albopictus*. In this section, we focus on vertebrate breath- and skin-derived semiochemicals that trigger behavioral events.

The need for a blood meal for reproduction drives mosquito vectors to seek and bite vertebrate hosts, including humans. Evidence for this behavioral trait comes from the first discovery implicating carbon dioxide (CO_2) as an olfactory cue for mosquitoes (109). A century after this discovery, a plethora of mosquito semiochemicals from different chemical classes have been identified in the *Aedes* mosquito host-seeking process (**Table 1**).

BREATH INFOCHEMICALS

CO_2 represents the most well-known breath semiochemical of importance in the sensory ecology of many blood-feeding insects. In the behavioral sequence of events, it serves both as an activator of flight activity and a long-range attractant prompting movement toward a suitable host (35, 126). Research has suggested that, as a generic cue emitted by all vertebrates, CO_2 is a poor indicator of host selection. Its importance in *Ae. albopictus* has not been studied. Nonetheless, its kairomonal effect in the chemical ecology of blood-feeding mosquitoes is unrivalled by any odorant identified to date (126). Other breath constituents, such as acetone, octenol, and ammonia (48), elicit attraction in *Ae. aegypti* only when combined with CO_2 (48, 126). Thus, the search for a CO_2 agonist (activating OSNs in the maxillary palp) in *Ae. aegypti* and perhaps *Ae. albopictus* remains a priority in the advancement and use of odor-baited technology in surveillance and control (discussed below). Octenol exists in two diastereomeric forms [(*R*)-1-octen-3-ol and (*S*)-1-octen-3-ol], documented to elicit sensory specificity and differential behavioral responses in both *Aedes* mosquitoes (30, 64). However, the exact role of octenol in attraction, landing, or probing needs to be resolved.

VERTEBRATE SKIN-DERIVED INFOCHEMICALS

The earliest record of vertebrate skin odors serving as infochemicals for mosquitoes was in 1968 (1). Since then, studies have revealed that skin odor is the primary driver of differential mosquito attraction to humans and discrimination from other animals (34, 36, 124). Carboxylic acids, aldehydes, alcohols, and ketones dominate the human skin volatile profile (15, 92). *Aedes* mosquitoes respond to these four classes of semiochemicals and, to a lesser extent, low-molecular-weight nitrogenous compounds such as ammonia. **Table 1** lists a selection of the behaviorally active compounds found in laboratory, mesocosm, and field assays.

Disease vectors tend to orient and land on a host to consume a blood meal. How do mosquitoes discriminate between hosts? Behavioral and chemical analyses of human odor identified the acids 2-ketoglutaric acid and L-lactic acid as landing attractants (13) and the latter as a diagnostic cue for *Ae. aegypti* to distinguish humans from nonhuman animals (120). However, the domestic form of *Ae. aegypti* prefers human odor because it recognizes the human-specific compound 6-methyl-5-hepten-2-one (sulcatone) (75). Human and animal odors evoke differential activity in the brain of *Ae. aegypti* because of selective tuning to the aldehydes decanal and undecanal, which are abundant in human odor (146). Recently, skin-derived carboxylic acids were implicated in the differential attraction of *Ae. aegypti* to humans (34). Likewise, the concentrations of human skin–derived aldehydes are important in the sensory ecology of *Ae. aegypti* as attractants or repellents (16). These findings suggest that the olfactory cues that mediate intra- and interspecific host discrimination may be affected by exposure of humans to conditions such as starvation, resting, perspiration, and pathogen infection.

Apart from humans, and despite the strong innate anthropophilic tendency, other vertebrate hosts also contribute to the *Ae. aegypti* host-seeking process, facilitated by different ecological conditions and host abundance (123). However, the chemical basis for host switch remains poorly elucidated. Tchouassi et al. (124) identified the monkey skin–derived compound cyclohexanone as an important signature cue for *Aedes* mosquitoes to seek nonhuman primates; in field tests, this compound synergized the attraction of CO_2 to attract various *Aedes* mosquitoes, including

Table 1 Semiochemicals behaviorally tested in laboratory and field assays

Behavior type	Chemical class	Semiochemical	Source	Mosquito species	Activity	Lab or field	Reference(s)
Blood host seeking	Gas	CO_2	Breath	*Aedes aegypti*	Flight activator, attractant	Field	32
		Ammonia	Skin odor or breath	*Ae. aegypti*	Repellent	Lab and field	138
	Carboxylic acid	Pentadecanoic acid	Human skin	*Aedes albopictus*	Repellent	Lab	16
		Hexanoic acid	Human skin	*Ae. albopictus*, *Ae. aegypti*	Attractant	Lab and field	92, 143
		Ammonia + lactic acid + hexanoic acid + 3-methyl-1-butanol + cyclopentanone	Synthetic blend	*Ae. albopictus*	Attractant	Lab and field	143
		Lactic acid + 2-ketoglutaric acid (pyruvic acid)	Human skin	*Ae. aegypti*	Landing attractant	Lab	13
		BG-lure (ammonia + L-lactic acid + hexanoic acid)	Human skin	*Ae. aegypti*, *Ae. albopictus*	Attractant	Field	66, 106, 138
		C1-C3, C5-C6, C8-C10, C12, C14, C16, C18, C20	Synthetic	*Ae. albopictus*	Attractant	Lab	114
		C4, C7, C11, C15, C19	Synthetic	*Ae. albopictus*	Repellent	Lab	114
		BG-lure + (*R*)-1-octen-3-ol	Synthetic	*Ae. albopictus*	Decreased attraction of females without CO_2	Field	106
	Cyclic ketone	Cyclohexanone	Monkey skin	*Ae. aegypti*	Attractant	Lab and field	124
		6-Methyl-5-hepten-2-one (sulcatone)	Human skin	*Ae. aegypti*	Attractant, repellent	Lab and field	72, 124
		Butanone, 2-pentanone, 3-pentanone	Human skin	*Ae. aegypti*	Attractant	Lab	17
		Geranylacetone	Human skin	*Ae. aegypti*	Repellent	Lab	16
		Acetoin (3-hydroxy-2-butanone)	Human skin	*Ae. aegypti*	Attractant	Lab	146
		Acetone	Breath	*Ae. aegypti*	Attractant	Lab	5, 48
		δ-Undecalactone, δ-decalactone	Breath	*Ae. aegypti*	Repellent	Lab	79
		Acetophenone	Skin microbiota of flavivirus-infected humans and mice	*Ae. aegypti*	Attractant	Lab	145
	Aldehyde	Octanal, nonanal, decanal	Human hand volatile	*Ae. aegypti*	Reduced flight activity and attraction	Lab	72
		Decanal and undecanal	Human skin odor	*Ae. aegypti*	Attractant	Lab	146

(*Continued*)

Table 1 ***(Continued)***

Behavior type	Chemical class	Semiochemical	Source	Mosquito species	Activity	Lab or field	Reference(s)
	Phenolic	Blend (4-methylphenol + 4-ethylphenol + phenol + indole)	Rat skin odor	*Ae. albopictus*	Attractant	Lab and field	37
	Alcohol	(*R*)-1-octen-3-ol, *R/S* octenol	Human skin, breath, sweat	*Ae. aegypti*, *Ae. albopictus*	Attractant or repellent	Lab and field	64, 106
	Sulfide	Lactic acid + acetone + dichloromethane + dimethyl disulfide	Human skin, breath	*Ae. aegypti*	Attractant	Lab	14
Oviposition	Alkane	n-Heneicosane	Larval cuticle, synthetic	*Ae. aegypti*	Pheromone, attractant	Lab	8, 78
	Terpene	Eugenol, citronellal, thymol, cineole, pulegone, linalool, trans-anethole	Synthetic	*Ae. aegypti*	Allomonal, deterrent	Lab	134
		β-Pinene, borneol, camphor, borneol acetate	Synthetic	*Ae. aegypti*	Attractant	Lab	134
	Carboxylic acid	Caproic acid (hexanoic acid)	Synthetic	*Ae. aegypti*	Stimulant	Lab	91
		(*Z*)-9-hexadecanoic acid	Synthetic, larval cuticle	*Ae. aegypti*	Stimulant	Lab	91
		Nonanoic acid, tetradecanoic acid, methyl tetradecanoate	Bamboo-associated bacteria	*Ae. aegypti*	Stimulant	Lab	98, 115
		Dodecanoic acid, (*Z*)-9-hexadecenoic acid	*Ae. aegypti* eggs	*Ae. aegypti*	Attractant	Lab	46
		Nonanoic, octanoic, decanoic, undecanoic, pentanoic, and hexanoic acids	Bacteria associated with organic infusions	*Ae. aegypti*	Repellent	Lab	59
		Isovaleric acid	Larvae and pupae	*Ae. aegypti*	Repellent	Lab	19
	Ester	Methyl-dodecanoate, methyl tetradecanoate, methyl (*Z*)-9-hexadecenoate, methyl-hexadecanoate, methyl (*Z*)-9-octadecenoate, methyl octadecanoate	Eggs	*Ae. aegypti*	Repellent	Lab	46
		Hexadecyl pentanoate, tetradecyl heptanoate, tridecyl octanoate	Synthetic	*Ae. aegypti*, *Ae. albopictus*	Repellent	Lab	115
		Propyl octadecanoate	Synthetic	*Ae. aegypti*	Attractant	Lab	115

(Continued)

Table 1 (*Continued*)

Behavior type	Chemical class	Semiochemical	Source	Mosquito species	Activity	Lab or field	Reference(s)
	Aldehyde	Nonanal	Synthetic	*Ae. aegypti*	Stimulant, attractant	Lab and field	20, 38
		Nonanal, decanal, benzothiazole, skatole, *p*-cresol, limonene, indole	Plant infusions	*Ae. aegypti*	Stimulant, attractant	Lab and field	107
		Decanal + skatole or decanal + *p*-cresol	Plant infusions	*Ae. aegypti*	Stimulant, attractant	Lab and field	107
	Alcohol	Geosmin	Microbiota of water habitat, beetroot peels	*Ae. aegypti*	Attractant	Lab and field	76
	Indole	3-Methylindole	Synthetic, grass infusions	*Ae. aegypti*	Attractant, repellent	Lab	8, 45
	Phenolic	4-Methylphenol, phenol	Synthetic	*Ae. aegypti*	Attractant	Lab	8
Mating	Cyclohexenone	2,6,6-Trimethylcyclohex-2-ene-1,4-dione	Male and female *Ae. aegypti*	*Ae. aegypti*	Aggregation pheromone that elicits a swarming-like flight in males	Lab	24, 41
	Cyclohexanone	2,2,6-Trimethylcyclohexane-1,4-dione	Female *Ae. aegypti*	*Ae. aegypti*	Aggregation pheromone that attracts females	Lab	24, 41
	Alkyl-phenylketone	1-(4-Ethylphenyl) ethanone	Male and female *Ae. aegypti*	*Ae. aegypti*	Aggregation pheromone that attracts females	Lab	41
	Carboxylic acid	Decanoic acid	Synthetic	*Ae. albopictus* (male)	Male attractant	Lab	24
Plant seeking	Terpenes	Linalool, dehydrolinalool	Synthetic	*Ae. aegypti*	Repellent (spatial)	Lab	65
		β-Myrcene, (*E*)-β-ocimene, linalool oxide	*Pithecellobium dulce*, *Senna uniflora*, *Hibiscus heterophyllus*	*Ae. aegypti*	Attractant	Lab and field	86, 88
	Benzenoids	Benzyl alcohol and indole	*P. dulce*, *S. uniflora*, *H. heterophyllus*	*Ae. aegypti*	Not tested	Not tested	88
	Aldehydes	Nonanal, lilac aldehyde	*Platanthera obtusata* orchid	*Ae. aegypti*	Attractant	Lab	68

Ae. aegypti. *Aedes albopictus* is attracted to rat odors and constituents of the crude odor, including phenol, 4-methylphenol, 4-ethylphenol, and indole (37). The benzenoid ketone, acetophenone, isolated from microbiota associated with the skin odors of flavivirus-infected mice and humans, was found to be a potent attractant for *Ae. aegypti* (145), suggesting that individuals infected with a virus are more attractive to mosquitoes. Examination of more nontraditional hosts could reveal new insight into olfactory interactions of these *Aedes* vectors and pathogen spread (124), which may lead to identification of novel semiochemicals.

OVIPOSITION SITE SELECTION

Finding a suitable site to lay eggs is critical to the survival of an insect species; gravid female mosquitoes lay their eggs in a suitable aquatic site (82, 139). Gravid females must navigate chemical cues released from these sites to lay their eggs. Beyond oviposition, gravid females may also associate ovipositional chemical cues to the nutritional qualities of these sites to ensure the fitness of their progeny. Given the natural histories of these two *Aedes* species as natural and container breeders, understanding the physiochemical and biotic characteristics of the aquatic site should help define their chemical ecology of oviposition.

Both *Aedes* species lay eggs in a wide range of human-fabricated water containers and natural habitats. These egg-laying sites are critical to offspring survival and determinant of adult population dynamics (139). The most decisive cues in oviposition site selection have been difficult to decipher. Physiochemical factors (e.g., container type, color, size, shape, and volume; fill method; temperature; pH; lid type; exposure to sun) have been described in relation to container larval productivity (29, 123, 139, 142). Sources of olfactory cues released from these sites include plant infusions, conspecific and heterospecific larvae, and microorganisms (82), although how these sources interact to define specific site choice is less well understood.

Plant infusions and their microbial breakdown products mediate adult mosquito egg-laying decisions. They influence the growth of microbes used as food for developing larvae. Microbial culture experiments and chemical analysis identified a blend of the bacterial-derived chemicals composed of carboxylic acids and their methyl esters as attractive to *Ae. aegypti* (7, 98, 115) (**Table 1**). Bacterial species and concentration may influence the quality and role of the chemical signal released, but this possibility will require additional research. Laboratory and field assays identified the alcohol geosmin from cyanobacteria as an attractant for *Ae. aegypti* (76). Most of these olfactory semiochemicals are medium-molecular-weight, less volatile chemicals; therefore, they may serve as reliable signature cues for females to identify oviposition sites. Given the different classes of chemicals identified, comparative studies are needed to identify the most potent individual or synergistic oviposition attractants. Low-molecular-weight, water-soluble organic compounds may play a role in mosquito oviposition site selection, and whether they serve as contact oviposition semiochemicals for gravid females is unknown. Previous work has demonstrated the presence of contact chemoreceptors in the mouthparts and legs of gravid females of *Ae. albopictus* (130), but their importance in the chemical ecology of this mosquito species is unknown.

Apart from bacteria, other microbes, such as fungi, and their odors may influence oviposition of gravid females. It is thought that certain fungi, such as entomopathogenic fungi, could modify the chemical composition of oviposition sites to make them either attractive or repellent to mosquitoes (112). This work is more advanced in malaria mosquitoes than in dengue vectors; in malaria vectors, fungi such as *Bacillus sphaericus* and *Bacillus thuringiensis* var. *israelensis* are widely used in vector control and known to cause larval death within 48 hours (43, 74). It has been proposed that the fungi-derived odors that attract mosquitoes to lay eggs in infected sites may provide benefits to fungi for their propagation (84).

The presence of immature conspecifics in a breeding site is a stronger attractive signal for gravid *Ae. aegypti* than either abundant food or potential competitors (139). It is anticipated that immature-derived compounds could offer species-specific attraction as pheromones. Examples include the hydrocarbon *n*-heneicosane, isolated from the larval cuticle of *Ae. aegypti* and implicated in laboratory and field assays as stimulating and attracting gravid females (8, 78). Additional studies are needed to determine whether *n*-heneicosane is specific to the cuticle of *Ae. aegypti* or a generalist chemical in the cuticle of other arthropods, including *Ae. albopictus* (50), and plants (82). Chemical analysis of egg and larval extracts identified carboxylic acids and methyl esters as mediating oviposition responses of *Ae. aegypti* gravid females (7, 46). Nonetheless, gaps exist in demonstrations of their presence in the emissions of water-containing immatures through headspace sampling collections.

The presence and influence of certain aquatic-inhabiting organisms in the mosquito oviposition process have been demonstrated. For instance, gravid *Ae. aegypti* females are attracted to odors released by the crustacean *Mesocyclops longisetus*, which has been used as a biological control agent for mosquitoes (22). Compounds identified in the odors of this crustacean include the monoterpenes 3-carene and α-terpinene and the sesquiterpenes α-copaene, α-cedrene, and δ-cadinene (129). Remarkably, water that had been conditioned with carpet shells (*Paphia undulate*) and giant tiger prawns (*Penaeus monodon*) attracted gravid *Ae. albopictus* females (128). These organisms are thought to release odors to attract ovipositing mosquitoes (as in mangrove ecosystems with vegetation) so that they can eat their larvae. The developmental stage, source, and composition of these chemicals and their applications in vector control await full elucidation.

MATING: SWARM AND MATING CUES AND THE ROLE OF HOST ODORS

In both *Aedes* species, mating usually occurs in male-dominated swarms, near a blood-meal host where females are attracted to copulate (57). However, the factors and mechanisms that underlie this process are not adequately understood. Acoustic cues produced by females through their wing beats are the primary signals that attract males to copulate (25, 26, 77). Behavioral and physiological analyses indicate that *Ae. aegypti* can respond to sound up to 10 m away (77). Additionally, chemical cues have also been the subject of intense research. Fawaz et al. (41) reported evidence of aggregation pheromones impacting swarm formation of *Ae. aegypti*. Chemical analysis of odors collected from confined adults of both sexes followed by behavioral assays identified 2,6,6-trimethylcyclohex-2-ene-1,4-dione, 2,2,6-trimethylcyclohexane-1,4-dione (found in females only), and 1-(4-ethylphenyl) ethenone as pheromones mediating swarm formation. However, only 2,6,6-trimethylcyclohex-2-ene-1,4-dione stimulated male swarming behavior (41), indicating the importance of olfactory cues in the reproductive biology of *Aedes* mosquitoes. Laboratory and field assays showed that swarming *Ae. aegypti* males responded to host odors (21, 57), but the mediating chemical cues were not identified. Males can be captured in traps baited with synthetic host-associated volatiles (6, 133). This may be associated with the adaptation of males to use hosts for finding mates. *Aedes aegypti* male captures increased with an increase in the number of mice used as bait (69), although it is unclear whether the response was related to increased CO_2 output (emitted by more mice) or their skin volatiles. In *Ae. aegypti*, optimal attraction to human odor depended on the male mating status. Mated males responded more strongly to human odors than their unmated counterparts (31). These findings suggest that males respond to vertebrate host kairomones (96, 137). Cuticular hydrocarbons have been proposed as sex pheromones in several mosquito species including *Ae. aegypti* (58). Wang et al. (135) found distinct profiles of extracts of different life stages of *Ae. aegypti* following chemical analysis, although the behavioral values of the constituents were not analyzed. *Aedes aegypti* and *Ae. albopictus* engage in mating activities (otherwise known as reproductive interference or satyrization) in the laboratory and at low rates in the field (131), but the offspring are generally nonviable. The cues involved in such a heterospecific behavior should be a subject of further research.

PLANT FEEDING AND ASSOCIATED OLFACTORY CUES

Like most mosquito species, adults of both sexes of these *Aedes* species require a sugar meal as an energy source for survival and various behavioral activities such as flight and reproduction; males are exclusive sugar feeders (87, 88, 100). *Aedes aegypti* could contribute to plant reproductive success as a pollinator, as has been reported in field studies (68). Sugar sources are mainly plant derived, including from plant tissues, ripe fruits, tree sap, and honeydew (83, 95). Plant feeding associations in these vectors have largely been determined through detection of fructose in the gut via biochemical assays (cold-anthrone test) (88, 121, 136). Advances in DNA-based approaches have improved our knowledge of specific plant species important in the trophic habits of *Ae. aegypti* (88, 136). Such DNA-based approaches and behavioral studies (83) have revealed the preference for certain plant species, but whether this behavior is related to plant nutritional content (28, 110) or other benefits (e.g., vectoring ability) remains unclear. Plant selection could be facilitated by the mosquito's sense of smell, a possibility that should be further investigated.

The study of the chemical ecology of plant feeding in these vectors is in its infancy. Few studies have identified olfactory cues of plant origin that mediate attraction to and discrimination among certain plant species by *Ae. aegypti* (68, 88). In electrophysiological studies of mosquito–host plant interactions, *Ae. aegypti* was found to detect the benzenoids benzyl alcohol and indole released in its preferred host plant volatiles, in addition to the monoterpenes β-myrcene and (E)-β-ocimene (88). Furthermore, the monoterpene linalool oxide attracted *Ae. aegypti* in both laboratory and field trials (86, 90), and it may attract *Ae. albopictus*, given that it attracts other vectors like malaria mosquitoes (60), although this remains to be confirmed in future studies. Since linalool oxide exists in diastereomeric forms, it is unknown whether there are species- and sex-specific differences in *Aedes* responses to these chemicals. Lahondère et al. (68) demonstrated that the discrimination of *Platanthera obtusata* from other sympatric *Platanthera* species by *Ae. aegypti* has a chemical basis that is strongly mediated by the compounds nonanal and lilac aldehyde. Both floral scent compounds are robustly detected in the mosquito antennae and attract this mosquito and other mosquito species in laboratory assays. Field assays are required to confirm the semiochemical roles of these compounds in *Ae. aegypti* chemical ecology.

Plants identified as repellent for mosquitoes in chemical ecology studies are scarce. Most studies report the screening of plant essential oils, obtained by hydrodistillation, whose formulations are compared with the protection times found for the synthetic mosquito repellent DEET (*N*, *N*-diethyl-*m*-toluamide) (65, 73). Despite DEET not being a semiochemical, its repellency has been shown to be olfactory based (122). Similar methods can be used to establish the mode of action of mosquito semiochemicals that are repellent.

GENETIC MECHANISMS INFLUENCING MOSQUITO OLFACTORY BEHAVIORS

The distinct genetic forms of *Ae. aegypti* vary in their specialization on humans and their selection of oviposition sites. In contrast, *Ae. albopictus* exhibits more relaxed (plastic) habits in these behaviors. Studies have revealed the underlying mechanisms that enable these mosquitoes to recognize and discriminate humans from other animals and other nutrient sources.

Research found a direct link between olfactory receptors and odor sensing in these and other mosquito species (18, 47, 71, 101). The olfactory receptors located within hair-like sensilla on the antennae and, to a lesser extent, maxillary palps and proboscis (101) are of three distinct types: ORs, ionotropic receptors (IRs), and gustatory receptors. As in other insects, ORs form heterodimers with a coreceptor to aid binding to single odorant molecules and/or to blends of odorant molecules (18, 47, 71, 101). *Aedes aegypti* possesses 110 receptors, while *Ae. albopictus* is predicted to have 158 (18, 27). Mosquito receptors are narrowly or broadly tuned to respond to specific odorants belonging to different classes (101). How differences in the number of ORs between the species contribute to behavioral differences is less well defined.

Both ORs and IRs seem to play a critical role in mosquito host discrimination. McBride et al. (75) demonstrated that the preference for human over animal odors in the *Ae. aegypti* domestic form has a genetic basis associated with differential expression of the olfactory receptor gene (*AaegOr4*) that recognizes the human-specific odorant sulcatone (6-methyl-5-hepten-2-one). A recent study showed that *Ae. aegypti* discriminated between humans based on skin-derived carboxylic acid levels, which were abundant in attractive individuals and sensed by the ionotropic receptors *Ir8a*, *Ir25a*, and *Ir76b* (34, 102). Mutant *Ae. aegypti* with loss of *Ir8a* generated through the gene editing technique CRISPR/Cas9 had reduced mosquito attraction to humans and their odor (34).

Attention is growing on efforts to gain a deeper understanding of neural processing that controls mosquito behavioral responses by recording and characterizing activity of individual glomeruli in the antennal lobe in response to odor stimuli. A striking example of this is the study of the neural basis of specialization on humans over animal hosts by domestic *Ae. aegypti.* In vivo calcium imaging experiments revealed distinct activation of olfactory glomeruli by human and animal odors within the *Ae. aegypti* antennal lobe (146). Further studies revealed that the human-sensitive glomerulus was selectively tuned to the long-chain aldehydes decanal and undecanal, which were enriched in human odor. Both odorants were found to enhance long-range host-seeking behavior in wind tunnel assays. A similar neural basis of mosquito discrimination in oviposition and nectar-seeking behaviors has been described recently. In *Aedes* spp. mosquitoes, including *Ae. aegypti*, specific odorants such as nonanal and lilac aldehyde mediated plant nectar choice and discrimination of *Platanthera* orchid species by differentially activated specific antennal glomeruli (LC2 and AM2) (68). Both odorants, which vary in relative abundance in the volatile emissions, appear to drive differential attraction among sympatric species of *Platanthera* orchids, yet they share the same scent constituents. A similar glomerular (PD3) response to geosmin, an oviposition attractant, was recently demonstrated in *Ae. aegypti* (76), indicating the existence of a single olfactory circuitry in biological processes.

OR systems also mediate plant nectar–feeding signaling in mosquitoes, as has been described in the malaria vector *Anopheles gambiae* (23) and is only beginning to be elucidated in *Aedes* mosquitoes (144). To date, olfactory receptor neurons responsive to plant volatiles such as α-pinene and α-thujone have been identified in *Ae. aegypti* (47, 74), but the associated receptors are not known, as is the case for many other plant-derived attractants. Given that some odorants are stereoisomers (e.g., linalool oxide), there is a need to define their sensitivity and specificity to specific ORs. Gaps exist in our understanding of the mechanisms that underlie olfactory sensing in oviposition site choice in these mosquito species (76). Recently, a maternally heritable and zygotic effect was demonstrated in response to dissolved oxygen that has allowed the domestic *Ae. aegypti* to selectively breed in human-provided artificial containers with higher oxygen content than in tree holes (80). Whether there is a link between higher oxygen content and microbial communities in these aquatic environments and, in turn, an influence of oxygen content on the chemical ecology of this mosquito species is unknown.

Olfactory learning can contribute to a mosquito's ability to discriminate among odors, hosts, and oviposition sites. In *Ae. aegypti*, Vinauger et al. (132) showed that the relationship between learning experience and host preference had a neurophysiological basis dependent on dopamine-1 receptor signaling in the antennal lobes. Curiously, while odors like 1-octen-3-ol could be learned, others, such as β-myrcene and benzyl alcohol, could not be learned. Likewise, learned responses of dengue virus–infected gravid *Ae. aegypti* varied between *p*-cresol and skatole, and loss of olfactory response to the latter correlated with altered gene expression in the mosquito's head (45). While mosquitoes may learn to associate specific odors with rewards or aversive behaviors, the findings suggest a heterogeneity in encoding different odors into memory, which needs to be resolved. More experiments may clarify which constituents of host or habitat odors, perhaps in combination, could be involved in learning association, since volatiles emitted by such substrates are composed of complex mixtures of compounds.

It is clear from these studies that, in the quest for survival, *Ae. aegypti* uses olfaction to find human and plant hosts, and it has developed robust neural and molecular mechanisms to locate, process, and discriminate odor stimuli to explore these resources. The available literature is skewed toward *Ae. aegypti*, and we are only beginning to appreciate the similar mechanisms in *Ae. albopictus*. In addition, the receptors responsive to other odor substrates (plants, oviposition sites) and associated cues are yet to be elucidated. The genetic architecture of odor sensing is extremely complex, and specific behavioral responses to odor stimuli may depend on multiple genes interacting with environmental factors, which necessitates studies on the mechanisms for sensing odor contrast in different ecological landscapes. The divergent behaviors inherent in the species call for comparative studies to distill and identify specific targets in neural circuits to guide targeted strategies to disrupt resource-seeking behaviors in these mosquitoes, even as the feasibility and utility of such an approach remain to be investigated.

MICROBIAL INFLUENCE OF OLFACTORY CUES AND VECTOR BEHAVIORAL RESPONSES

Increasing evidence indicates that microorganisms (symbionts and pathogens) produce volatiles that influence mosquito responses to hosts (plant and vertebrates) and oviposition sites. Vertebrate hosts infected with the malaria parasites have different host odor profiles that are more attractive to mosquito vectors; this suggests that the pathogen may be manipulating the host odor to attract its vector (33, 67). Likewise, Zhang et al. (145) demonstrated that infection with the flaviviruses (dengue and Zika viruses) increased *Ae. aegypti* attraction to virus-infected mice and humans. Behavioral and chemical analyses revealed that the attractive response in *Ae. aegypti* was associated with enhanced production of acetophenone by skin microbiota of virus-infected humans and mice. The results of this study represent an unusual example of a multitrophic chemical signaling relationship (host–vector–pathogen–bacterial microbe) and a coevolutionary adaptation whereby mosquito-transmitted flaviviruses can manipulate host skin microbiota to produce a scent that attracts mosquitoes. This could be applicable to other pathosystems, including plants.

Another example of microbial influence in volatile emission is geosmin, an oviposition attractant associated with microbes present in the larval aquatic habitat (76). Plant nectar feeding is an obligate behavior of both *Aedes* species (88, 136), although interaction with nectar microbes is poorly understood. Bacteria and fungi are well-known inhabitants of the floral nectar of many angiosperm species worldwide that mosquitoes host seek for sugars (52, 81, 94). These microbes can alter a suite of traits in floral nectar important for the plant's signaling to insects, including its volatile emission profile (103). Of these microbes, bacteria have attracted more attention than fungi and viruses because of the volatile organic compounds that they produce (52, 81, 94), which mediate specific behaviors of *Aedes* mosquitos, in particular oviposition (see the section titled Oviposition Site Selection). The roles of fungi and viruses in vector behavior are yet to be fully explored. Microbes such as yeast can secrete byproducts of fermentation, including CO_2, that function as signals for mosquitoes to identify food sources. Cumulatively, such microbe-induced volatiles can be used in vector monitoring. They can also serve as biomarkers for disease diagnosis or predictors of disease infection status in humans.

DENGUE SURVEILLANCE AND CONTROL USING INFOCHEMICALS

Preventive control of dengue relies on controlling the vector populations; to date, no effective tools exist to sustainably prevent human infections. New solutions are urgently required to address the threat posed by dengue, which has increased over the past two decades. Interest in vector biology has continued to grow, and semiochemicals that mediate vector interaction with fitness-enhancing resources are among the promising tools that could be deployed in vector surveillance and control.

Vector surveillance is considered a cornerstone of arboviral disease risk assessment (62). It assesses the existing epidemiological situation to predict the likelihood of outbreaks in humans and preemptively deploy appropriate interventions (111). In mosquito-based arbovirus surveillance, trapping techniques are used to monitor adult mosquito populations. Next, captured mosquitoes are tested for virus infection via virus-isolation, immunoglobulin, or polymerase chain reaction assays. To improve dengue monitoring, given that high populations of vectors usually precede human disease cases, chemical attractants can be deployed in existing traps to increase *Aedes* catches (39). High rates of mosquito catch could maximize virus detection probability, which is critical during the interepidemic period, normally characterized by low vector numbers and sporadic transmission foci (53, 125). This is also helpful in areas of potential disease emergence, where there may be lower vector densities (harder to detect) but high susceptibility (due to naive immune population).

Research on olfactory cues has been central to ongoing efforts to develop more effective surveillance tools. However, only a few of these olfactory semiochemicals have been field tested to understand their ecological relevance. To date, the synthetic host-derived attractants that have been evaluated are only effective when they are synergized with CO_2 (126). The cost and logistical constraints make the use of CO_2 impractical in routine surveillance in remote and resource-limited settings. In theory, the use of plant-derived volatiles as lures could target adult mosquitoes of both sexes and females of different physiological states (unfed, gravid, blood fed) (85, 89). However, this hypothesis remains to be tested and validated in field trials. Additionally, it remains to be determined whether plant-derived attractants may be more sensitive in attracting arbovirus-infected vectors than other attractants. Research on CO_2 alternatives is a priority in advancing odor-bait technologies that utilize host-derived attractants in disease surveillance or control.

It has been proposed that the sensitivity of virological surveillance in mosquitoes can be improved by targeting gravid mosquito cohorts. Because of their previous blood-host encounters, targeting gravid females increases the likelihood of virus detection in them. Knowledge of olfactory cues involved in oviposition site choice could similarly be exploited to increase gravid female collections in existing traps (e.g., ovitraps and *Aedes* gravid traps). Surprisingly, the chemical signature of an ideal *Ae. aegypti* or *Ae. albopictus* oviposition site is unknown, and no promising attractants exist that have been rigorously validated in field trials (**Table 1**).

Attractants can be used to mass trap *Aedes*, a pull system that could be combined with sublethal doses of insecticide, biopesticide, or sticky adhesive in an attract and kill strategy (12). For example, CO_2-based barrier trap systems (i.e., removal outdoor trapping) have been shown to reduce the human-biting rate of *Ae. albopictus* (4). Another example is the use of lethal traps that suppress adult populations of container-breeding mosquitoes like *Ae. aegypti* and *Ae. albopictus* (**Table 2**). The highlighted shortcomings of some of these strategies have increased the urgency of developing and applying novel technologies that may optimize surveillance and control.

CONCLUSIONS AND PROSPECTS FOR FUTURE RESEARCH

Dengue and other *Aedes*-borne arboviral diseases are expanding rapidly across the globe, facilitated by a myriad of factors, among them climate change and human activities. These factors are likely to affect the chemical ecology of host seeking, oviposition, mating, and plant feeding of the key vectors of these diseases, which they depend on for survival. In this review, we show that, irrespective of the physiological stage, olfaction plays a major role in the behavioral ecology of the two driving vectors of dengue, *Ae. aegypti* and *Ae. albopictus*. These vectors have developed robust neural and molecular mechanisms to locate, process, and discriminate odor stimuli to explore these diverse resources. However, research remains to be conducted to unravel the full repertoire of olfactory cues used by these two vectors to survive in the human environment. Nonetheless, current knowledge on olfaction provides opportunities for developing tools and techniques for surveillance and control of these *Aedes* populations as part of disease management. Some of these (e.g., lethal traps, attractive toxic sugar baits, smart traps) have shown promise but require further large-scale evaluations in diverse settings. Control applications targeting genes that regulate the olfaction process in mosquitoes, as well as other developing or hypothetical applications highlighted in this review, need further research.

Increasingly, research is highlighting the importance of microorganisms in mediating the olfactory cues that influence mosquito interaction with different substrates and the ensuing behaviors. Human activities are impacting the planet's climate and ecosystems (i.e., the Anthropocene), in turn altering the distribution of mosquito vectors and interactions with microorganisms (pathogens and symbionts) and hosts (plants and vertebrates). The consequences could include changes in mosquito olfactory signaling. For instance, increasing levels of Anthropocenic ozone has been found to alter the configuration of male-specific pheromones in the fruit fly *Drosophila melanogaster* (61), an indication that climate change has a clear impact on mate recognition and pheromonal communication.

Thus, many unanswered questions remain in this Anthropocene Era. For example, how do xenobiotics such as organic and inorganic pollutants influence the olfactory profiles of oviposition sites? How does a climate change scenario, such as a rise in temperature, affect all of the behavioral attributes of the vector and the fitness of its progeny? Would an increase in the rate of dissolution of gases and certain environmental pollutants, and changes in microbial species composition, alter the semiochemical profiles mediating vector behavior? Finally, new and more robust polymer container materials are increasingly being introduced into the consumer market. The interactive effects between these new container materials and specific chemicals in water, such as adsorbed metal ions, may modulate interfacial affinity for certain microbial chemicals and environmental pollutants released into the aquatic environment. For example, plastic containers may degrade into particles, including secondary microplastics and nanoplastics, which may combine with certain container additives or microbial-derived chemicals to form complexes. When these complexes are released into the aquatic environment, mosquito larvae that are exposed to them may emerge as adults that are less or more susceptible to biorationals; these possibilities require further research.

Excitingly, the information gained from understanding chemical sensing systems in mosquitoes such as *Ae. aegypti* (75, 80, 142, 146) is helping us to understand the evolution of different populations or subspecies (e.g., Aaa versus Aaf) and how this evolution may shape adaptation in different environments and natural history traits including habitat and seasonal preferences.

Table 2 Emerging and proposed tools for *Aedes* surveillance and control

Technology	Description	Role of olfactory cues	Settings for appropriate use and/or limitations
Lethal trap (LT)	LTs represent an attract and kill strategy (population suppression) that exploits the ovipositing behavior of container-breeding mosquitoes.	The technique uses fermented infusions that emit volatiles that attract gravid female mosquitoes. Killing is achieved by the use of an adhesive strip or toxicant.	The technique has shown promise in suppressing *Aedes* population densities and disease incidence (12) but needs more large-scale trials in diverse disease settings. Infusions are cumbersome and produce an offensive smell that could hinder deployment in human dwellings. Identifying the oviposition attractants offers avenues to develop user-friendly synthetic lures for possible commercialization. Benefits of the LT system include being passive and low cost and having the potential for implementation by communities to control *Aedes* populations.
Attractive toxic sugar baits (ATSBs)	ATSBs represent an attract and kill method that targets both sexes of mosquitoes seeking a nectar source.	ATSBs employ fruit scents or visual cues as attractants (10, 117), sucrose solution to stimulate feeding, and an oral toxin or insecticide of low vertebrate toxicity (e.g., boric acid, eugenol, spinosad, dinotefuran, ivermectin) to kill mosquitoes.	ATSBs have been largely evaluated on *Aedes aegypti* and *Aedes albopictus* in lab, semifield, or small-scale trials (10, 104, 113, 117, 118, 127). Sugars alone are odorless, and cut flowers lose their potency to attract insects over time. Potent synthetic attractants (e.g., L-lactic, 1-octen-3-ol) are essential to augment bait effectiveness (113).
Smart traps	Smart traps integrate technological advances (e.g., geographic information systems) into a trap to estimate mosquito densities and can sort and identify mosquitoes to species level and sex. They can reveal spatiotemporal trends and areas of high *Aedes* infestations for timely decision making. Subsequent screening of viruses in trapped mosquitoes could employ (*a*) high-throughput technologies such as portable DNA sequencers (e.g., Nanopore MinION) as effective rapid diagnostic tools, with the added advantages of discriminating variants and gaining insights into the epidemiologic relevance of virus genetic variations (44), or (*b*) sugar-baited nucleic acid preservation cards (FTA cards) whereby, as infected vectors attempt to feed on the sugary solution in a trap, they expectorate viruses whose nucleic acids are trapped on the cards and then processed for testing (55).	To prevent fishing without bait, mosquitoes can be lured with potent attractants into traps to access FTA cards. Other traps that target oviposition behavior can be used (e.g., ovitraps, gravid traps).	Smart traps are suitable for worldwide-scale implementation with minimal infrastructure or expertise required, although they can be limited in certain settings without constant internet access. The sensitivity of trapping devices could be a key issue. The cost related to manpower for trap inspection and running molecular assays for virus detection could hamper large-scale deployment, especially in developing countries.

(*Continued*)

Table 2 (*Continued*)

Technology	Description	Role of olfactory cues	Settings for appropriate use and/or limitations
Sterile insect technique (SIT)	The SIT is a potential tool for area-wide pest management of mosquitoes based on the release of sterilized males (69). The monitoring of the abundance, distribution, movement, and ratio of released sterile and wild fertile males is a fundamental requirement for its successful implementation.	It is conceivable that olfactory cues that primarily mediate the exclusive plant-feeding habit in males could be exploited as attractants in this endeavor to monitor the establishment of released males, although no commercial lure exists. Potential chemical attractants could be combined with acoustic visual signals in sound traps to make this a reality (9).	The SIT is a species-specific and environment-friendly method for area-wide vector control. Strategies exist to enhance survival and mating competitiveness of released males in the wild. Investments have been made into tools for improved surveillance of male populations.
Microbiota-associated cues	Most host volatiles (human) are microbiota derived, and differences in microbiota composition correlate with human attractiveness to mosquitoes.	Skin microbiota (or diagnostic cue) could be re-engineered to alter the human scent composition, thereby minimizing exposure to mosquito bites and preventing the spread of mosquito-borne diseases. Sensitive monitoring techniques, such as use of unmanned aerial vehicles fitted with spectral sensors, could be developed to detect microbial profiles and olfactory fingerprints from potential breeding sites for interventions with environmentally friendly biocides against larvae.	Research investment is needed into defining the microbial signature cues of suitable breeding sites.
Molecular screens targeting olfactory receptors	High-throughput screening assays akin to pharmacologic drug discovery have been described to identify odors that modulate mosquito olfactory receptor function to specific behaviors (147). Advances in molecular olfaction and neurophysiology are expected to contribute to knowledge of specific codes underlying behavior in disease vectors and to aid in the identification of important attractive and aversive odorants.	Recent developments in genome editing tools, such as CRISPR-Cas9 RNA-guided nucleases, zinc finger nucleases, TALE-effector nucleases, and the GAL4-UAS system (101), provide opportunities to achieve these interventions. High-throughput screening assays can be used to identify synthetic and natural compounds that activate receptors associated with repellency or inhibit receptors associated with attraction. In addition, efforts are needed to develop a new generation of repellents that (*a*) block multiple chemosensory pathways to make humans invisible to mosquitoes or (*b*) overstimulate a specific chemosensory pathway for mosquitoes to avoid humans (101).	Knowledge of the specific receptors that enable mosquito attraction and repellency is required.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

D.P.T. is supported by a Wellcome Trust International Intermediate Fellowship (222005/Z/20/Z). We gratefully acknowledge financial support for this research from the following organizations and agencies: Combatting Arthropod Pests for Better Health, Food and Climate Resilience

(CAP-Africa; project number RAF-3058 KEN-18/0005) funded by the Norwegian Agency for Development Cooperation (Norad); the Swedish International Development Cooperation Agency (Sida); the Swiss Agency for Development and Cooperation (SDC); the Australian Centre for International Agricultural Research (ACIAR); the Federal Democratic Republic of Ethiopia; and the Government of the Republic of Kenya. The views expressed in this review do not necessarily reflect the official opinion of the donors.

LITERATURE CITED

1. Acree F Jr., Turner RB, Gouck HK, Beroza M, Smith N. 1968. L-lactic acid: a mosquito attractant isolated from humans. *Science* 161:1346–47
2. Agha SB, Tchouassi DP. 2022. Urbanisation of *Aedes* mosquito populations and evolution of arboviral disease risk in Africa. *Curr. Opin. Insect Sci.* 54:100988
3. Ahmed A, Abubakr M, Sami H, Mahdi I, Mohamed NS, Zinsstag J. 2022. The first molecular detection of *Aedes albopictus* in Sudan associates with increased outbreaks of chikungunya and dengue. *Int. J. Mol. Sci.* 23:11802
4. Akhoundi M, Jourdain F, Chandre F, Delaunay P, Roiz D. 2018. Effectiveness of a field trap barrier system for controlling *Aedes albopictus*: a "removal trapping" strategy. *Parasit. Vectors* 11:101
5. Amann A, de Lacy Costello B, Miekisch W, Schubert J, Buszewski B, et al. 2014. The human volatilome: volatile organic compounds (VOCs) in exhaled breath, skin emanations, urine, feces and saliva. *J. Breath Res.* 8:034001
6. Amos BA, Ritchie SA, Carde RT. 2020. Attraction versus capture II: efficiency of the BG Sentinel trap under semifield conditions and characterizing response behaviors of male *Aedes aegypti* (Diptera: Culicidae). *J. Med. Entomol.* 57:1539–49
7. Arbaoui AA, Chua TH. 2014. Bacteria as a source of oviposition attractant for *Aedes aegypti* mosquitoes. *Trop. Biomed.* 31:134–42
8. Baak-Baak CM, Rodríguez-Ramírez AD, García-Rejón JE, Ríos-Delgado S, Torres-Estrada JL. 2013. Development and laboratory evaluation of chemically-based baited ovitrap for the monitoring of *Aedes aegypti*. *J. Vector Ecol.* 38:175–81
9. Balestrino F, Iyaloo DP, Elahee KB, Bheecarry A, Campedelli F, et al. 2016. Sound trap for *Aedes albopictus* (Skuse) male surveillance: response analysis to acoustic and visual stimuli. *Acta Trop.* 164:448–54
10. Barbosa DS, Rodrigues MM, Silva AA. 2019. Evaluation of attractive toxic sugar baits (ATSB) against *Aedes aegypti* (Diptera: Culicidae) in laboratory. *Trop. Biomed.* 36:578–86
11. Barredo E, DeGennaro M. 2020. Not just from blood: mosquito nutrient acquisition from nectar sources. *Trends Parasitol.* 36(5):473–84
12. Barrera R. 2022. New tools for *Aedes* control: mass trapping. *Curr. Opin. Insect Sci.* 3:100942
13. Bello JE, Cardé RT. 2022. Compounds from human odor induce attraction and landing in female yellow fever mosquitoes (*Aedes aegypti*). *Sci. Rep.* 12:15638
14. Bernier UR, Kline DL, Allan SA, Barnard DR. 2007. Laboratory comparison of *Aedes aegypti* attraction to human odors and to synthetic human odor compounds and blends. *J. Am. Mosq. Control Assoc.* 23:288–93
15. Bernier UR, Kline DL, Barnard D, Schreck C, Yost RA. 2000. 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.* 72:747–56
16. Bernier UR, Kline D, Posey KH. 2006. Human emanations and related natural compounds that inhibit mosquito host-finding abilities. In *Insect Repellents: Principles, Methods, and Uses*, ed. M Debboun, S Frances, D Strickman, pp. 77–100. Boca Raton, FL: CRC Press
17. Bernier UR, Kline DL, Schreck CE, Yost RA, Barnard DR. 2002. 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.* 18:186–95
18. Bohbot J, Pitts RJ, Kwon HW, Rützler M, Robertson HM, Zwiebel LJ. 2007. Molecular characterization of the *Aedes aegypti* odorant receptor gene family. *Insect Mol. Biol.* 16:525–37

19. Boullis A, Mulatier M, Delannay C, Héry L, Verheggen F, Vega-Rúa A. 2021. Behavioural and antennal responses of *Aedes aegypti* (l.) (Diptera: Culicidae) gravid females to chemical cues from conspecific larvae. *PLOS ONE* 16:e0247657
20. Braga IA, Gomes AC, Nelson M, Mello RC, Bergamaschi DP, de Souza JM. 2000. Comparative study between larval surveys and ovitraps to monitor populations of *Aedes aegypti*. *Rev. Soc. Bras. Med. Trop.* 33:347–53
21. Cabrera M, Jaffe K. 2007. An aggregation pheromone modulates lekking behavior in the vector mosquito *Aedes aegypti* (Diptera: Culicidae). *J. Am. Mosq. Control Assoc.* 23:1–10
22. Calliari D, Sanz K, Martınez M, Cervetto G, Gomez M, Basso C. 2003. Comparison of the predation rate of freshwater cyclopoid copepod species on larvae of the mosquito *Culex pipiens*. *Med. Vet. Entomol.* 17:339–42
23. Carey AF, Carlson JR. 2011. Insect olfaction from model systems to disease control. *PNAS* 108:12987–95
24. Carraretto D, Soresinetti L, Rossi I, Malacrida AR, Gasperi G, Gomulski LM. 2022. Behavioural responses of male *Aedes albopictus* to different volatile chemical compounds. *Insects* 13:290
25. Cator LJ, Arthur BJ, Harrington LC, Hoy RR. 2020. Harmonic convergence in the love songs of the dengue vector mosquito. *Science* 323:1077–79
26. Cator LJ, Arthur BJ, Ponlawat A, Harrington LC. 2011. Behavioral observations and sound recordings of free-flight mating swarms of *Ae. aegypti* (Diptera: Culicidae) in Thailand. *J. Med. Entomol.* 48:941–46
27. Chen XG, Jiang X, Gu J, Xu M, Wu Y, et al. 2015. Genome sequence of the Asian tiger mosquito, *Aedes albopictus*, reveals insights into its biology, genetics, and evolution. *PNAS* 112:5907–15
28. Chen Z, Kearney CM. 2015. Nectar protein content and attractiveness to *Aedes aegypti* and *Culex pipiens* in plants with nectar/insect associations. *Acta Trop.* 146:81–88
29. Chumsri A, Pongmanawut P, Tina FW, Jaroensutasinee M, Jaroensutasinee K. 2018. Container types and water qualities affecting on number of *Aedes* larvae in Trang province, Thailand. *Walailak Procedia* 2018:st43
30. Cook JI, Majeed S, Ignell R, Pickett JA, Birkett MA, Logan JG. 2011. Enantiomeric selectivity in behavioural and electrophysiological responses of *Aedes aegypti* and *Culex quinquefasciatus* mosquitoes. *Bull. Entomol. Res.* 101:541–50
31. da Silva Paixão K, de Castro Pereira I, Lopes Alves Bottini L, Eiras ÁE. 2015. Volatile semiochemical-conditioned attraction of the male yellow fever mosquito, *Aedes aegypti*, to human hosts. *J. Vector Ecol.* 40:1–6
32. de Ázara TM, Degener CM, Roque RA, Ohly JJ, Geier M, Eiras ÁE. 2013. The impact of CO_2 on collection of *Aedes aegypti* Linnaeus and *Culex quinquefasciatus* Say by BG-Sentinel traps in Manaus, Brazil. *Mem. Inst. Oswaldo Cruz* 108:229–32
33. De Moraes CM, Stanczyk NM, Betz HS, Pulido H, Sim DG, et al. 2014. Malaria-induced changes in host odors enhance mosquito attraction. *PNAS* 111:11079–84
34. De Obaldia ME, Morita T, Dedmon LC, Boehmler DJ, Jiang CS, et al. 2022. Differential mosquito attraction to humans is associated with skin-derived carboxylic acid levels. *Cell* 185:4099–116
35. Dekker T, Geier M, Cardé RT. 2005. Carbon dioxide instantly sensitizes female yellow fever mosquitoes to human skin odours. *J. Exp. Biol.* 208:2963–72
36. Dekker T, Steib B, Cardé RT, Geier M. 2002. L-lactic acid: a human-signifying host cue for the anthropophilic mosquito *Anopheles gambiae*. *Med. Vet. Entomol.* 16:91–98
37. Díaz-Santiz E, Rojas JC, Casas-Martínez M, Cruz-López L, Malo EA. 2020. Rat volatiles as an attractant source for the Asian tiger mosquito, *Aedes albopictus*. *Sci. Rep.* 10:5170
38. Eiras AE, Resende MC, Acebal JL, Paixao KS. 2016. New cost-benefit of Brazilian technology for vector surveillance using trapping system. In *Malaria*, ed. FH Kasenga, art. 78781. London: IntechOpen
39. Eldridge BF. 1987. Strategies for surveillance, prevention, and control of arbovirus diseases in western North America. *Am. J. Trop. Med. Hyg.* 37:77S–86S
40. Faull K, Williams C. 2015. Intraspecific variation in desiccation survival time of *Aedes aegypti* (L.) mosquito eggs of Australian origin. *J. Vector Ecol.* 40:292–300
41. Fawaz EY, Allan SA, Bernier UR, Obenauer PJ, Diclaro JW. 2014. Swarming mechanisms in the yellow fever mosquito: Aggregation pheromones are involved in the mating behavior of *Aedes aegypti*. *J. Vector Ecol.* 39:347–54

42. Ferguson NM. 2018. Challenges and opportunities in controlling mosquito-borne infections. *Nature* 559:490–97
43. Floore TG. 2006. Mosquito larval control practices: past and present. *J. Am. Mosq. Control Assoc.* 22:527–33
44. Fouet C, Kamdem C. 2019. Integrated mosquito management: Is precision control a luxury or necessity? *Trends Parasitol.* 35:85–95
45. Gaburro J, Paradkar PN, Klein M, Bhatti A, Nahavandi S, Duchemin JB. 2018. Dengue virus infection changes *Aedes aegypti* oviposition olfactory preferences. *Sci. Rep.* 8:13179
46. Ganesan K, Mendki MJ, Suryanarayana MVS, Prakash S, Malhotra RC. 2006. Studies of *Aedes aegypti* (Diptera: Culicidae) ovipositional responses to newly identified semiochemicals from conspecific eggs. *Austr. J. Entomol.* 45:75–80
47. Ghaninia M, Ignell R, Hansson BS. 2007. Functional classification and central nervous projections of olfactory receptor neurons housed in antennal trichoid sensilla of female yellow fever mosquitoes, *Aedes aegypti*. *Eur. J. Neurosci.* 26:1611–23
48. Ghaninia M, Majeed S, Dekker T, Hill SR, Ignell R. 2019. Hold your breath—differential behavioural and sensory acuity of mosquitoes to acetone and carbon dioxide. *PLOS ONE* 14:e0226815
49. Gloria-Soria A, Ayala D, Bheecarry A, Calderon-Arguedas O, Chadee DD, et al. 2016. Global genetic diversity of *Aedes aegypti*. *Mol. Ecol.* 25:5377–95
50. Gonzalez PV, Gonzalez Audino PA, Masuh HM. 2014. Electrophysiological and behavioural response of *Aedes albopictus* to n-heinecosane, an ovipositional pheromone of *Aedes aegypti*. *Entomol. Exp. Appl.* 151:191–97
51. Gratz NG. 2004. Critical review of the vector status of *Aedes albopictus*. *Med. Vet. Entomol.* 18:215–27
52. Grice EA, Segre JA. 2011. The skin microbiome. *Nat. Rev. Microbiol.* 9:244–53
53. Gu W, Unnasch TR, Katholi CR, Lampman R, Novak RJ. 2008. Fundamental issues in mosquito surveillance for arboviral transmission. *Trans. R. Soc. Trop. Med. Hyg.* 102:817–22
54. Gubler DJ. 2012. The economic burden of dengue. *Am. J. Trop. Med. Hyg.* 86:743–44
55. Hall-Mendelin S, Ritchie SA, Johansen CA, Zborowski P, Cortis G, et al. 2010. Exploiting mosquito sugar feeding to detect mosquito-borne pathogens. *PNAS* 107:11255–59
56. Harrington LC, Fleisher A, Ruiz-Moreno D, Vermeylen F, Wa CV, et al. 2014. Heterogeneous feeding patterns of the dengue vector, *Aedes aegypti*, on individual human hosts in rural Thailand. *PLOS Negl. Trop. Dis.* 8:e3048
57. Hartberg W. 1971. Observations on the mating behaviour of *Aedes aegypti* in nature. *Bull. World Health Organ.* 45:847–50
58. Horn GL, Priestman AA. 2002. The chemical characterization of the epicuticular hydrocarbons of *Aedes aegypti* (Diptera: Culicidae) *Bull. Entomol. Res.* 92:287–94
59. Hwang YS, Schultz GW, Axelrod H, Kramer WL, Mulla MS. 1982. Ovipositional repellency of fatty acids and their derivatives against *Culex* and *Aedes* mosquitoes. *Environ. Entomol.* 11:223–36
60. Jacob JW, Tchouassi DP, Lagat ZO, Mathenge EM, Mweresa CK, Torto B. 2018. Independent and interactive effect of plant- and mammalian- based odors on the response of the malaria vector, *Anopheles gambiae*. *Acta Trop.* 185:98–106
61. Jiang N, Chang H, Weisflog J, Eberl F, Veit D, et al. 2023. Ozone exposure disrupts insect sexual communication. *Nat. Commun.* 14:1186
62. Kamau WW, Sang R, Rotich G, Agha SB, Menza N, et al. 2023. Patterns of *Aedes aegypti* abundance, survival, human-blood feeding and relationship with dengue risk, Kenya. *Front. Trop. Dis.* 4:1113531
63. Kamgang B, Nchoutpouen E, Simard F, Paupy C. 2012. Notes on the blood feeding behavior of *Aedes albopictus* (Diptera: Culicidae) in Cameroon. *Parasit. Vectors* 5:57
64. Kline DL, Allan SA, Bernier UR, Welch CH. 2007. Evaluation of the enantiomers of 1-octen-3-ol and 1-octyn-3-ol as attractants for mosquitoes associated with a freshwater swamp in Florida, U.S.A. *Med. Vet. Entomol.* 21:323–31
65. Kline DL, Bernier UR, Posey KH, Barnard DR. 2003. Olfactometric evaluation of spatial repellents for *Aedes aegypti*. *J. Med. Entomol.* 40:463–67

66. Krockel U, Rose A, Eiras AE, Geier M. 2006. New tools for surveillance of adult yellow fever mosquitoes: comparison of trap catches with human landing rates in an urban environment. *J. Am. Mosq. Control Assoc.* 22:229–38
67. Lacroix R, Mukabana WR, Gouagna LC, Koella JC. 2005. Malaria infection increases attractiveness of humans to mosquitoes. *PLOS Biol.* 3:e298
68. Lahondère C, Vinauger C, Okubo RP, Wolff GH, Chan JK, et al. 2020. The olfactory basis of orchid pollination by mosquitoes. *PNAS* 117:708–16
69. Le Goff G, Damiens D, Payet L, Ruttee AH, Jean F, et al. 2016. Enhancement of the BG-Sentinel trap with varying number of mice for field sampling of male and female *Aedes albopictus* mosquitoes. *Parasit. Vectors* 9:514
70. Leroy EM, Nkoghe D, Ollomo B, Nze-Nkogue C, Becquart P, et al. 2009. Concurrent chikungunya and dengue virus infections during simultaneous outbreaks, Gabon. *Emerg. Infect. Dis.* 15:591–93
71. Liu H, Liu T, Xie L, Wang X, Deng Y, et al. 2016. Functional analysis of Orco and odorant receptors in odor recognition in *Aedes albopictus*. *Parasit. Vectors* 9:363
72. Logan JG, Birkett MA, Clark SJ, Powers S, Seal NJ, et al. 2008. Identification of human-derived volatile chemicals that interfere with attraction of *Aedes aegypti* mosquitoes. *J. Chem. Ecol.* 34:308–22
73. Lovinella I, Mandoli A, Luceri C, D'Ambrosio M, Caputo B, et al. 2023. Cyclic acetals as novel long-lasting mosquito repellents. *J. Agric. Food Chem.* 71(4):2152–59
74. Lutz EK, Lahondère C, Vinauger C, Riffell JA. 2017. Olfactory learning and chemical ecology of olfaction in disease vector mosquitoes: a life history perspective. *Curr. Opin. Insect Sci.* 20:75–83
75. McBride CS, Baier F, Omondi AB, Spitzer SA, Lutomiah J, et al. 2014. Evolution of mosquito preference for humans linked to an odorant receptor. *Nature* 515:222–27
76. Melo N, Wolff GH, Costa-da-Silva AL, Arribas R, Triana MF, et al. 2020. Geosmin attracts *Aedes aegypti* mosquitoes to oviposition sites. *Curr. Biol.* 30:127–34
77. Menda G, Nitzany EI, Shamble PS, Wells A, Harrington LC, et al. 2019. The long and short of hearing in the mosquito *Aedes aegypti*. *Curr. Biol.* 29:709–14
78. Mendki MJ, Ganesan KSP, Suryanarayana MVS, Malhotra RC, Rao KM, Vaidyanathaswamy R. 2000. Heneicosane: an oviposition-attractant pheromone of larval origin in *Aedes aegypti* mosquito. *Curr. Sci.* 78:1295–96
79. Menger DJ, Van Loon JJA, Takken W. 2014. Assessing the efficacy of candidate mosquito repellents against the background of an attractive source that mimics a human host. *Med. Vet. Entomol.* 28:407–13
80. Metz HC, Miller AK, You J, Akorli J, Avila FW, et al. 2023. Evolution of a mosquito's hatching behavior to match its human-provided habitat. *Am. Nat.* 201(2):200–14
81. Morath SU, Hung R, Bennett JW. 2012. Fungal volatile organic compounds: a review with emphasis on their biotechnological potential. *Fungal Biol. Rev.* 26:73–83
82. Mulatier M, Boullis A, Vega-Rúa A. 2022. Semiochemical oviposition cues to control *Aedes aegypti* gravid females: state of the art and proposed framework for their validation. *Parasit. Vectors* 15:228
83. Müller GC, Xue RD, Schlein Y. 2011. Differential attraction of *Aedes albopictus* in the field to flowers, fruits and honeydew. *Acta Trop.* 118:45–49
84. Mwingira V, Mboera LE, Dicke M, Takken W. 2020. Exploiting the chemical ecology of mosquito oviposition behavior in mosquito surveillance and control: a review. *J. Vector Ecol.* 45:155–79
85. Nyasembe VO, Tchouassi DP, Kirwa HK, Foster WA, Teal PEA, et al. 2014. Development and assessment of plant-based synthetic odor baits for surveillance and control of malaria vectors. *PLOS ONE* 9:e89818
86. Nyasembe VO, Tchouassi DP, Mbogo CM, Sole CL, Pirk C, Torto B. 2015. Linalool oxide: generalist plant-based lure for mosquito disease vectors. *Parasit. Vectors* 8:581
87. Nyasembe VO, Tchouassi DP, Muturi MN, Pirk CW, Sole CL, Torto B. 2021. Plant nutrient quality impacts survival and reproductive fitness of the dengue vector *Aedes aegypti*. *Parasit. Vectors* 14:4
88. Nyasembe VO, Tchouassi DP, Pirk CWW, Sole CL, Torto B. 2018. Host plant forensics and olfactory-based detection in Afro-tropical mosquito disease vectors. *PLOS Negl. Trop. Dis.* 12:e0006185
89. Nyasembe VO, Torto B. 2014. Volatile phytochemicals as mosquito semiochemicals. *Phytochem. Lett.* 8:196–201

90. Omondi WP, Owino EA, Odongo D, Mwangangi JM, Torto B, Tchouassi DP. 2019. Differential response to plant- and human-derived odorants in field surveillance of the dengue vector, *Aedes aegypti*. *Acta Trop*. 200:105163
91. Ong SQ, Jaal Z. 2015. Investigation of mosquito oviposition pheromone as lethal lure for the control of *Aedes aegypti* (L.) (Diptera: Culicidae). *Parasit. Vectors* 8:28
92. Owino EA, Sang R, Sole CL, Pirk C, Mbogo C, Torto B. 2014. Field evaluation of natural human odours and the biogent-synthetic lure in trapping *Aedes aegypti*, vector of dengue and chikungunya viruses in Kenya. *Parasit. Vectors* 7:451
93. Paton RS, Bonsall MB. 2019. The ecological and epidemiological consequences of reproductive interference between the vectors *Aedes aegypti* and *Aedes albopictus*. *J. R. Soc. Interface* 16:20190270
94. Peach DA, Carroll C, Meraj S, Gomes S, Galloway E, et al. 2021. Nectar-dwelling microbes of common tansy are attractive to its mosquito pollinator, *Culex pipiens* L. *BMC Ecol. Evol.* 21:29
95. Peach DA, Gries R, Young N, Lakes R, Galloway E, et al. 2019. Attraction of female *Aedes aegypti* (L.) to aphid honeydew. *Insects* 10:43
96. Pitts RJ, Mozūraitis R, Gauvin-Bialecki A, Lemperiere G. 2014. The roles of kairomones, synomones and pheromones in the chemically-mediated behaviour of male mosquitoes. *Acta Trop*. 132:S26–34
97. Ponlawat A, Harrington LC. 2005. Blood feeding patterns of *Aedes aegypti* and *Aedes albopictus* in Thailand. *J. Med. Entomol.* 42(5):844–49
98. Ponnusamy L, Xu N, Nojima S, Wesson DM, Schal C, Apperson CS. 2008. Identification of bacteria and bacteria-associated chemical cues that mediate oviposition site preferences by *Aedes aegypti*. *PNAS* 105:9262–67
99. Powell JR, Tabachnick WJ. 2013. History of domestication and spread of *Aedes aegypti*—a review. *Mem. Inst. Oswaldo Cruz* 108:11–17
100. Qualls WA, Xue RD, Beier JC, Müller GC. 2013. Survivorship of adult *Aedes albopictus* (Diptera: Culicidae) feeding on indoor ornamental plants with no inflorescence. *Parasitol. Res.* 112:2313–18
101. Raji JI, DeGennaro M. 2017. Genetic analysis of mosquito detection of humans. *Curr. Opin. Insect Sci.* 20:34–38
102. Raji JI, Melo N, Castillo JS, Gonzalez S, Saldana V, et al. 2019. *Aedes aegypti* mosquitoes detect acidic volatiles found in human odor using the IR8a pathway. *Curr. Biol.* 29:1253–62
103. Rering CC, Beck JJ, Hall GW, McCartney MM, Vannette RL. 2018. Nectar-inhabiting microorganisms influence nectar volatile composition and attractiveness to a generalist pollinator. *New Phytol*. 220:750–59
104. Revay EE, Müller GC, Qualls WA, Kline DL, Naranjo DP, et al. 2014. Control of *Aedes albopictus* with attractive toxic sugar baits (ATSB) and potential impact on non-target organisms in St. Augustine, Florida. *Parasitol. Res.* 113:73–79
105. Rey JR, Nishimura N, Wagner B, Braks MAH, O'Connell SM, Lounibos LP. 2006. Habitat segregation of mosquito arbovirus vectors in south Florida. *J. Med. Entomol.* 43:1134–41
106. Roiz D, Duperier S, Roussel M, Boussès P, Fontenille D, et al. 2016. Trapping the tiger: efficacy of the novel BG-Sentinel 2 with several attractants and carbon dioxide for collecting *Aedes albopictus* (Diptera: Culicidae) in Southern France. *J. Med. Entomol.* 53:460–65
107. Roque RA. 2007. *Avaliação de atraentes de oviposição, identificados em infusões de capim colonião* (Panicum maximum) *para fêmeas de* Aedes aegypti *(L. 1762) (Diptera: Culicidae) em condições de semicampo ecampo*. PhD Thesis, Univ. Fed. Minas Gerais, Belo Horizonte, Braz.
108. Rose NH, Sylla M, Badolo A, Lutomiah J, Ayala D, et al. 2020. Climate and urbanization drive mosquito preference for humans. *Curr. Biol.* 30:3570–79
109. Rudolfs W. 1922. Chemotropism of mosquitoes. *Bull. N. J. Agric. Exp. Stations* 367:4–23
110. Samson DM, Qualls WA, Roque D, Naranjo DP, Alimi T, et al. 2013. Resting and energy reserves of *Aedes albopictus* collected in common landscaping vegetation in St. Augustine, Florida. *J. Am. Mosq. Control Assoc.* 30:231–36
111. Sang R, Lutomiah J, Chepkorir E, Tchouassi DP. 2022. Evolving dynamics of *Aedes*-borne diseases in Africa: a cause for concern. *Curr. Opin. Insect Sci.* 53:100958
112. Scholte EJ, Knols BG, Samson RA, Takken W. 2004. Entomopathogenic fungi for mosquito control: a review. *J. Insect Sci.* 4:19

113. Scott-Fiorenzano JM, Fulcher AP, Seeger KE, Allan SA, Kline DL, et al. 2017. Evaluations of dual attractant toxic sugar baits for surveillance and control of *Aedes aegypti* and *Aedes albopictus* in Florida. *Parasit. Vectors* 10:9

114. Seenivasagan T, Guha L, Parashar BD, Agrawal OP, Sukumaran D. 2014. Olfaction in Asian tiger mosquito *Aedes albopictus*: flight orientation response to certain saturated carboxylic acids in human skin emanations. *Parasitol. Res.* 113:1927–32

115. Sharma KR, Seenivasagan T, Rao AN, Ganesan K, Agarwal OP, et al. 2008. Oviposition responses of *Aedes aegypti* and *Aedes albopictus* to certain fatty acid esters. *Parasitol. Res.* 103:1065–73

116. Simard F, Nchoutpouen E, Toto JC, Fontenille D. 2005. Geographic distribution and breeding site preference of *Aedes albopictus* and *Aedes aegypti* (Diptera: Culicidae) in Cameroon, Central Africa. *J. Med. Entomol.* 42:726–31

117. Sippy R, Rivera GE, Sanchez V, Heras F, Morejón B, et al. 2020. Ingested insecticide to control *Aedes aegypti*: developing a novel dried attractive toxic sugar bait device for intra-domiciliary control. *Parasit. Vectors* 13:78

118. Sissoko F, Junnila A, Traore MM, Traore SF, Doumbia S, et al. 2019. Frequent sugar feeding behavior by *Aedes aegypti* in Bamako, Mali makes them ideal candidates for control with attractive toxic sugar baits (ATSB). *PLOS ONE* 14:e0214170

119. Sota T, Mogi M. 1992. Interspecific variation in desiccation survival time of *Aedes* (*Stegomyia*) mosquito eggs is correlated with habitat and egg size. *Oecologia* 90:353–58

120. Steib BM, Geier M, Boeckh J. 2001. The effect of lactic acid on odour-related host preference of yellow fever mosquitoes. *Chem. Senses* 26:523–28

121. Swan T, Ritmejerytė E, Sebayang B, Jones R, Devine G, et al. 2021. Sugar prevalence in *Aedes albopictus* differs by habitat, sex and time of day on Masig Island, Torres Strait, Australia. *Parasit. Vectors* 14:520

122. Syed Z, Leal WS. 2008. Mosquitoes smell and avoid the insect repellent DEET. *PNAS* 105(36):13598–603

123. Tchouassi DP, Agha SB, Villinger J, Sang R, Torto B. 2022. The distinctive bionomics of *Aedes aegypti* populations in Africa. *Curr. Opin. Insect Sci.* 54:100986

124. Tchouassi DP, Jacob JW, Ogola EO, Sang R, Torto B. 2019. *Aedes* vector-host olfactory interactions in sylvatic and domestic dengue transmission environments. *Proc. R. Soc. B* 286:20192136

125. Tchouassi DP, Sang R, Sole CL, Bastos ADS, Teal PEA, et al. 2013. 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.* 7:e2007

126. Tchouassi DP, Wanjiku C, Torto B. 2022. Host-derived attractants for surveillance and control of mosquitoes. In *Sensory Ecology of Disease Vectors*, ed. R Ignell, CR Lazzari, MG Lorenzo, SR Hill, pp. 851–77. Wageningen, Neth.: Wageningen Acad. Publ.

127. Tenywa FS, Musa JJ, Musiba RM, Swai JK, Mpelepele AB, et al. 2022. Evaluation of an ivermectin-based attractive targeted sugar bait (ATSB) against *Aedes aegypti* in Tanzania. *Wellcome Open Res.* 7:4

128. Thavara U, Tawatsin A, Chompoosri J. 2004. Evaluation of attractants and egg-laying substrate preference for oviposition by *Aedes albopictus* (Diptera: Culicidae). *J. Vector Ecol.* 29:66–72

129. Torres-Estrada JL, Rodríguez MH, Cruz-López L, Arredondo-Jimenez JI. 2001. Selective oviposition by *Aedes aegypti* (Diptera: Culicidae) in response to *Mesocyclops longisetus* (Copepoda: Cyclopoidea) under laboratory and field conditions. *J. Med. Entomol.* 38:188–92

130. Trexler JD, Apperson CS, Schal C. 1998. Laboratory and field evaluations of oviposition responses of *Aedes albopictus* and *Aedes triseriatus* (Diptera: Culicidae) to oak leaf infusions. *J. Med. Entomol.* 35:967–76

131. Tripet F, Lounibos LP, Robbins D, Moran J, Nishimura N, Blosser EM. 2011. Competitive reduction by satyrization? Evidence for interspecific mating in nature and asymmetric reproductive competition between invasive mosquito vectors. *Am. J. Trop. Med. Hyg.* 85:265–70

132. Vinauger C, Lahondère C, Wolff GH, Locke LT, Liaw JE, et al. 2018. Modulation of host learning in *Aedes aegypti* mosquitoes. *Curr. Biol.* 28:333–44

133. Visser TM, De Cock MP, Hiwat H, Wongsokarijo M, Verhulst NO, Koenraadt CJ. 2020. Optimisation and field validation of odour-baited traps for surveillance of *Aedes aegypti* adults in Paramaribo, Suriname. *Parasit. Vectors* 13:121

134. Waliwitiya R, Kennedy CJ, Lowenberger CA. 2009. Larvicidal and oviposition-altering activity of monoterpenoids, trans-anithole and rosemary oil to the yellow fever mosquito *Aedes aegypti* (Diptera: Culicidae). *Pest Manag. Sci.* 65:241–48

135. Wang F, Delannay C, Goindin D, Deng L, Guan S, et al. 2019. Cartography of odor chemicals in the dengue vector mosquito (*Aedes aegypti* L., Diptera/Culicidae). *Sci. Rep.* 9:8510

136. Wanjiku C, Tchouassi DP, Sole CL, Pirk CWW, Torto B. 2021. Plant sugar feeding patterns of *Aedes aegypti* from dengue endemic and non-endemic areas of Kenya. *Med. Vet. Entomol.* 35:417–25

137. Wheelwright M, Whittle CR, Riabinina O. 2021. Olfactory systems across mosquito species. *Cell Tissue Res.* 383:75–90

138. Williams CR, Bergbauer R, Geier M, Kline DL, Bernier UR. 2006. Laboratory and field assessment of some kairomone blends for host-seeking *Aedes aegypti*. *J. Am. Mosq. Control Assoc.* 22:641–47

139. Wong J, Stoddard ST, Astete H, Morrison AC, Scott TW. 2011. Oviposition site selection by the dengue vector *Aedes aegypti* and its implications for dengue control. *PLOS Negl. Trop. Dis.* 5:e1015

140. Wooding M, Naudé Y, Rohwer E, Bouwer M. 2020. Controlling mosquitoes with semiochemicals: a review. *Parasit. Vectors* 13:80

141. World Health Organization. 2023. *Dengue and severe dengue*. Fact Sheet, World Health Organ., Geneva. **https://www.who.int/news-room/fact-sheets/detail/dengue-and-severe-dengue**

142. Xia S, Dweck HK, Lutomiah J, Sang R, McBride CS, et al. 2021. Larval sites of the mosquito *Aedes aegypti formosus* in forest and domestic habitats in Africa and the potential association with oviposition evolution. *Ecol. Evol.* 11:16327–43

143. Xie L, Yang W, Liu H, Liu T, Xie Y, et al. 2019. Enhancing attraction of the vector mosquito *Aedes albopictus* by using a novel synthetic odorant blend. *Parasit. Vectors* 12:382

144. Zeng F, Xu P, Leal WS. 2019. Odorant receptors from *Culex quinquefasciatus* and *Aedes aegypti* sensitive to floral compounds. *Insect Biochem. Mol. Biol.* 113:103213

145. Zhang H, Zhu Y, Liu Z, Peng Y, Peng W, et al. 2022. A volatile from the skin microbiota of flavivirus-infected hosts promotes mosquito attractiveness. *Cell* 185:2510–22

146. Zhao Z, Zung JL, Hinze A, Kriete AL, Iqbal A, et al. 2022. Mosquito brains encode unique features of human odour to drive host seeking. *Nature* 605:706–12

147. Zhu J, Arena S, Spinelli S, Liu D, Zhang G, et al. 2017. Reverse chemical ecology: olfactory proteins from the giant panda and their interactions with putative pheromones and bamboo volatiles. *PNAS* 114:E9802–10