Comparative Intelligence and Adaptive Behaviours of Anopheles versus Culex Mosquitoes: Implications for Enhanced Surveillance Efficiency and Innovative Vector Control Strategies

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ABSTRACT

This study provides a comprehensive analysis of the comparative intelligence and adaptive behaviors of Anopheles and Culex mosquitoes, two key genera involved in the transmission of significant vector-borne diseases such as malaria, dengue, West Nile virus, and filariasis. The paper explores how their cognitive abilities, including sensory processing, learning, memory, and decision-making, influence their survival strategies, host-seeking behaviors, and responses to control measures. While Anopheles mosquitoes primarily transmit malaria through specialized behaviors such as selective blood-feeding and host detection, Culex mosquitoes' exhibit broader host preferences and are implicated in the transmission of several other diseases, including West Nile virus. This review also addresses the behavioral adaptations of both genera in response to environmental pressures and control strategies, such as insecticides and repellents, emphasizing their evolving resistance to conventional methods. The implications of these adaptive behaviors for enhancing surveillance and vector control strategies are discussed, highlighting how a deeper understanding of mosquito cognition could improve control tactics. This study also suggests new approaches to mosquito control based on behavioral modification and cognitive disruption, proposing a shift towards more targeted, behavior-based interventions. Future research directions are outlined, focusing on the role of mosquito intelligence in disease transmission dynamics and the development of integrated, sustainable control strategies.

***Keywords**: Anopheles mosquitoes, Culex mosquitoes, behavioral adaptation, vector control strategies, mosquito intelligence*

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INTRODUCTION

Mosquitoes of the genera *Anopheles* and *Culex* are among the most important vectors of human diseases worldwide, contributing significantly to public health challenges. These species, while differing in ecological niches and behaviors, share a common role in the transmission of vector-borne diseases that result in considerable morbidity and mortality. The review focuses on these two genera, comparing their respective roles in disease transmission, particularly their significance in the spread of diseases such as malaria, dengue, West Nile virus, and lymphatic filariasis.

The *Anopheles* genus is globally recognized as the primary vector for the transmission of malaria, a life-threatening infectious disease caused by *Plasmodium* parasites. *Anopheles* mosquitoes, particularly *Anopheles gambiae* and *Anopheles stephensi*, are responsible for the majority of malaria transmission in sub-Saharan Africa, Asia, and parts of the Americas. Malaria affects hundreds of millions of people globally, with significant economic and health burdens, especially in low-income countries (González Pérez, 2023). Apart from malaria, *Anopheles* mosquitoes also contribute to the transmission of other diseases such as lymphatic filariasis, a parasitic infection caused by *Wuchereria bancrofti*, which can lead to debilitating symptoms like elephantiasis (Javed, 2021).

On the other hand, mosquitoes of the *Culex* genus, including species such as *Culex pipiens*, *Culex quinquefasciatus*, and *Culex tarsalis*, are vectors for a range of other important diseases, including West Nile virus, dengue fever, chikungunya, and lymphatic filariasis (Singh, Akhtar, & Gupta, 2024). *Culex* mosquitoes are particularly significant in temperate and tropical regions, where they act as the primary vectors for West Nile virus, a disease that has emerged as a significant health threat in North America and other parts of the world. Additionally, *Culex* mosquitoes play a critical role in transmitting lymphatic filariasis, which is endemic in many tropical and subtropical regions, particularly in Africa and Southeast Asia (Tyagi, 2025). Furthermore, the role of *Culex* mosquitoes in transmitting dengue and chikungunya has led to widespread outbreaks globally, particularly in urban environments where these species thrive (Branda *et al*., 2024).

Both *Anopheles* and *Culex* mosquitoes have profound implications for public health. *Anopheles* mosquitoes are primarily responsible for the transmission of malaria, a disease that kills over 400,000 people annually, most of whom are young children under the age of five in sub-Saharan Africa (Javed *et al*., 2021). *Culex* mosquitoes, although less deadly than *Anopheles*, still pose significant risks to human health by spreading diseases like West Nile virus and dengue, which cause millions of cases and deaths each year (Tyagi *et al*., 2025). The spread of these diseases places enormous burdens on health systems, economies, and communities, underlining the need for effective vector control strategies.

Why Intelligence and Adaptive Behavior Matter

The growing recognition of mosquito intelligence and adaptive behavior marks a conceptual shift in vector biology from viewing mosquitoes as passive carriers of pathogens to understanding them as cognitively competent organisms capable of dynamic interaction with complex ecological and anthropogenic systems. Intelligence in mosquitoes, although not analogous to vertebrate cognition, encompasses sensory integration, learning, memory, behavioral plasticity, and context-dependent decision-making. These traits are not peripheral; rather, they constitute the biological infrastructure that determines host selection, vector competence, environmental persistence, and resistance to control interventions (Figure 1).

Recent global dialogues on vector control emphasize that conventional approaches particularly those reliant on insecticides are increasingly constrained by behavioral adaptation and ecological change (Chareonviriyaphap et al., 2024; Zhang et al., 2024). The reframing of vector control strategies in the Asia-Pacific region underscores the necessity of accounting for behavioral plasticity in mosquitoes, particularly under conditions of rapid urbanization and climate variability. Intelligence and adaptive behavior thus matter because they directly influence how mosquitoes respond to human attempts at suppression, including insecticide-treated nets (ITNs), indoor residual spraying (IRS), environmental modification, and emerging genomic tools.

From a systems perspective, Reiter's (2025) AI Mirror Architecture, though conceptualized within artificial intelligence research, offers a useful heuristic for understanding mosquito environment interactions. The idea of layered sensory "mirrors" and conditioned resonance parallels the multi-layered feedback systems in mosquito ecology, where environmental cues (temperature, humidity, host density, chemical signals) are processed through sensory filters and behavioral conditioning. Mosquitoes adapt not merely through genetic mutation but through feedback-driven behavioral recalibration an ecological resonance between organism and environment. This analogy becomes particularly relevant as vector control increasingly integrates data science, genomics, and predictive modeling.

The genomic revolution has illuminated the molecular basis of behavioral traits and adaptation. De Marco (2025) highlights how data science and genomic studies are revealing gene networks associated with insecticide resistance, host preference, and environmental tolerance. Such findings complicate simplistic models of resistance evolution by showing that adaptive traits often emerge from polygenic architectures interacting with microbiomes and environmental stressors. The significance of intelligence, therefore, extends to the genomic scale: adaptive behavior is scaffolded by regulatory pathways responsive to ecological signals.

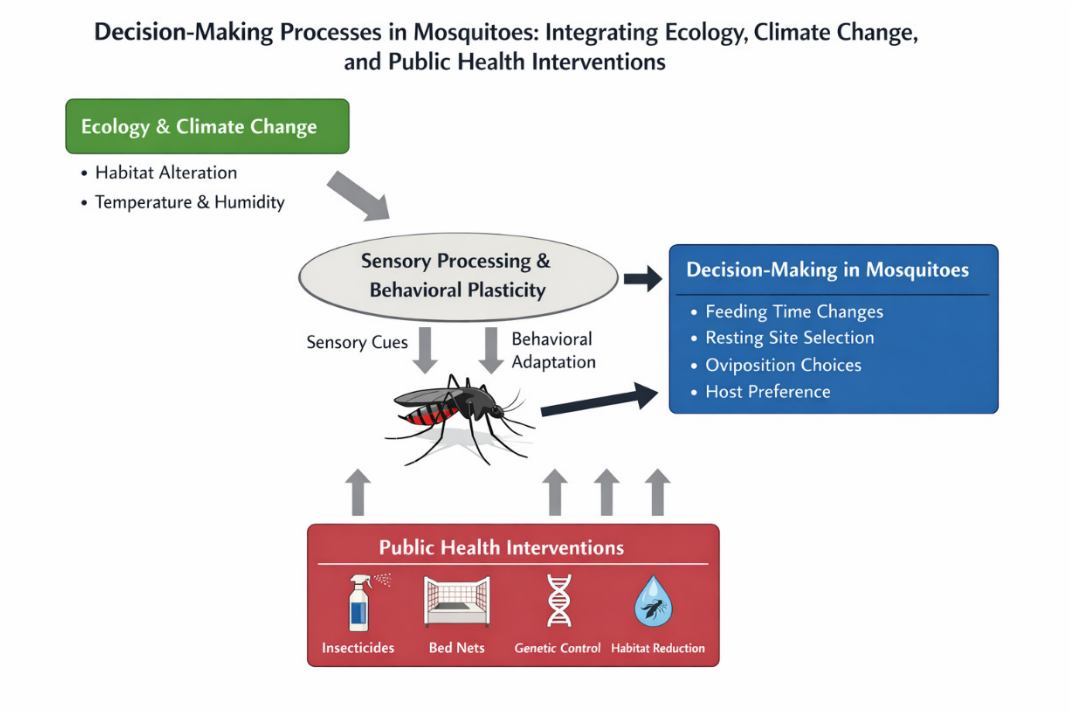

Figure 1: Decision-Making Processes in Mosquitoes for Health workers.

Climate change further intensifies the importance of behavioral flexibility. Zhang et al. (2024) and Abbasi (2026) argue that climate-driven shifts in temperature, precipitation, and extreme events are altering mosquito distribution, phenology, and breeding ecology. Adaptive behavioral responses—such as altered feeding times, expanded host range, or microhabitat selection mediate these transitions. Intelligence, in this context, functions as a buffer against environmental uncertainty, allowing mosquito populations to exploit newly suitable habitats or persist in marginal ones. Consequently, understanding adaptive behavior is indispensable for predicting geographic expansion and disease emergence.

Urbanization introduces another dimension. Joseph et al. (2024) demonstrate how urban typologies across the East African Community shape mosquito genera overlap and disease transmission dynamics. Urban landscapes are heterogeneous mosaics of microclimates, water storage systems, waste accumulation, and human density gradients. Mosquitoes navigating such environments must integrate diverse sensory and ecological signals. Their adaptive behaviors resting preferences, oviposition site selection, host switching are central determinants of urban transmission risk. Thus, intelligence is not an abstract trait; it materially shapes epidemiological patterns.

The One Health framework further situates mosquito adaptive behavior within interconnected human–animal–environment systems. Raji et al. (2025) emphasize integrative surveillance that bridges ecological and epidemiological data. Intelligent behavioral responses such as opportunistic feeding on multiple host species facilitate zoonotic spillover and pathogen amplification. Surveillance systems must therefore account not only for mosquito abundance but also for behavioral shifts that alter transmission networks.

Technological innovation in surveillance underscores this point. Mocq et al. (2026) demonstrate the use of digital PCR for early-warning detection of arboviruses in water and mosquito excreta. Such tools presume that mosquito behavior oviposition, aggregation, excretion patterns creates detectable environmental signatures. Intelligence and adaptive behavior influence these signatures; shifts in breeding site preference or dispersal behavior could alter surveillance efficacy. Therefore, behavioral understanding enhances not only control strategies but also diagnostic precision.

Integrated disease management approaches, such as those discussed for Zika virus (Izah et al., 2026), further illustrate why adaptive behavior matters. Successful integration of diagnostics, surveillance, and mosquito management depends on anticipating behavioral counter-adaptations. For example, if control measures reduce indoor biting, exophagic or crepuscular feeding behaviors may increase. Ignoring these cognitive and behavioral dimensions risks strategic obsolescence.

Ultimately, intelligence and adaptive behavior matter because they mediate the evolutionary arms race between humans and mosquitoes. Climate change, urbanization, globalization, and technological intervention have created a rapidly shifting ecological theatre. Mosquitoes persist not solely through genetic mutation but through behavioral plasticity, learning, and environmental attunement. A failure to integrate cognitive ecology into vector biology risks underestimating the resilience of these vectors. Conversely, embracing intelligence as a central analytical lens opens new interdisciplinary pathways merging genomics, data science, climate modeling, surveillance innovation, and One Health strategies toward more adaptive and anticipatory vector control.

Processing and Host Detection

Mosquito host detection represents one of the most sophisticated examples of multisensory integration among hematophagous insects. Sensory processing in mosquitoes involves the coordinated function of olfactory, visual, thermal, hygrosensory, and potentially infrared detection systems, all operating within dynamic ecological and temporal contexts. Far from being reflexive responders to carbon dioxide plumes, mosquitoes exhibit layered sensory hierarchies and context-dependent modulation that reflect neural specialization and behavioral plasticity.

At the molecular level, odorant reception constitutes the primary gateway to host detection. Leal (2025) details the functional and evolutionary architecture of insect odorant receptors (ORs), highlighting ligand specificity, receptor co-expression, and combinatorial coding strategies that enable discrimination among complex odor blends. In mosquitoes, this system allows detection of human-specific compounds such as lactic acid and other volatile organic molecules. Kordaczuk and Wojda (2026) extend this understanding by examining odorant-binding proteins (OBPs), which solubilize hydrophobic odorants and modulate immune responses. The dual sensory immune role of OBPs suggests that host detection and pathogen exposure are biologically intertwined processes.

Recent work by Lou et al. (2026) reveals temporal synchrony between human odor rhythms and mosquito olfactory preference, indicating that host attraction fluctuates with circadian variation in human scent profiles. This finding reframes host detection as temporally dynamic rather than static. Vinauger and Chandrasegaran (2024) similarly demonstrate context-specific variation in life history traits and behavior in Aedes aegypti, reinforcing that sensory responses are modulated by physiological state, reproductive status, and environmental conditions.

Comparative insights from other vectors strengthen mechanistic interpretation. Adden and Prieto-Godino (2026) describe the sensory ecology of tsetse flies, emphasizing neural integration pathways in the antennal lobe and higher-order brain centers. Although phylogenetically distinct, parallels in olfactory circuit organization suggest conserved strategies of cue integration among hematophagous Diptera. Kovacs (2024) documents host-foraging cues in stable flies, while Fischer et al. (2026) explore chemical ecology in arachnids, underscoring convergent evolution in hematophagous host detection systems. Thermal and infrared cues add additional sensory layers. Berthier and Schöllhorn (2026) describe infrared detection mechanisms in arthropods, offering theoretical grounding for heat-based orientation in mosquitoes. Thermal gradients, combined with humidity and CO_2 plumes, form a multisensory attractant field. Soman et al. (2026) conceptualize odor tracking as a multisensory behavior in which visual and mechanosensory inputs refine plume navigation. Thus, host detection is not linear but integrative, involving cross-modal calibration.

Neural and genetic tools now enable deeper interrogation of these processes. Rouyar et al. (2024) developed a transgenic line to characterize GABA-receptor expression in Aedes aegypti, facilitating analysis of inhibitory modulation in olfactory circuits. Such neurogenetic approaches reveal how sensory signals are filtered and prioritized, illuminating the neural substrates of behavioral choice. Emerging multi-omics research further expands this picture. Gao et al. (2026) demonstrate associations between gut microbiota composition and olfactory gene expression. This suggests a bidirectional relationship in which microbial communities modulate sensory sensitivity, potentially influencing host preference and vector competence. Sensory processing, therefore, is embedded within broader physiological networks.

Behavioral heterogeneity among mosquitoes is increasingly evident. Marrero et al. (2026) show that individual humans attract different mosquito species, indicating species-specific olfactory tuning and possibly learned preference. Jimenez-Vallejo et al. (2026) analyze drivers of indoor free-flight and resting behavior, linking sensory cues to spatial decision-making indoors. Wan et al. (2026) demonstrate that pathogen infection alters mosquito behavior in species-specific ways, potentially enhancing transmission through modified host-seeking patterns.

Technological applications also arise from this knowledge. Ventura et al. (2026) discuss the digitization of scent detection via OBP-based biosensors, illustrating how understanding mosquito olfaction can inform bio-inspired technologies.

Collectively, these studies demonstrate that sensory processing and host detection are central to mosquito ecology and epidemiology. The integration of olfactory, thermal, visual, and microbial cues, mediated by specialized neural circuits and modulated by environmental and physiological context, enables precise host localization. This sensory intelligence directly shapes biting rates, host specificity, and disease transmission dynamics. As vector control increasingly explores odor-based traps, spatial repellents, and behavioral disruption strategies, an advanced understanding of mosquito sensory ecology becomes indispensable.

Decision-Making and Adaptation to Control Measures

Mosquito decision-making and adaptation to control measures illustrate the dynamic interplay between evolutionary genetics, behavioral plasticity, ecological change, and public health intervention. The increasing complexity of mosquito-borne disease management reflects not only pathogen diversity but also the cognitive and adaptive capacities of vector populations. Surveillance reports from international conferences (Poinsignon et al., 2025) and regional reviews (Bogacka et al., 2026) emphasize that traditional control strategies face diminishing returns due to behavioral avoidance and insecticide resistance. Naik et al. (2023) document historical trends in India, revealing cyclical resurgence of diseases as vectors adapt to chemical pressures. Behavioral modifications such as earlier evening biting, outdoor feeding, or altered resting patterns constitute decision-making processes shaped by selective pressure. Climate change compounds these dynamics. Zhang et al. (2024) and Oziegbe et al. (2025) show that warming temperatures and altered rainfall patterns expand vector habitats and extend transmission seasons. Adaptive decision-making such as exploiting new breeding sites or shifting feeding times enables mosquitoes to capitalize on climatic shifts. Wei et al. (2026) highlight the broad disease spectrum influenced by these ecological transitions.

Mathematical models provide insight into these adaptive processes. Akinsunmade et al. (2026) integrate multi-environmental factors and intervention strategies into mosquito population models, demonstrating threshold effects and nonlinear responses to control measures. Baafi and Hurford (2025) further show how seasonality shapes population dynamics, implying that mosquito behavioral decisions are synchronized with environmental cycles. Such models underscore that adaptation operates at both individual and population scales.

Public health disruptions, such as the COVID-19 pandemic, illustrate the fragility of control systems. Lu et al. (2023) describe how interrupted vector control activities created ecological opportunities for mosquito resurgence. Decision-making at the mosquito level choosing oviposition sites or host environments intersects with human institutional decision-making, creating feedback loops.

Integrated management approaches are increasingly advocated. Kumar et al. (2024) argue for novel tools beyond conventional insecticides. Okafor et al. (2026) and Izah et al. (2026) emphasize sustainable, integrated disease management strategies incorporating environmental management, surveillance, and community engagement. Alqassim (2026) situates these challenges within neglected tropical diseases, stressing the importance of adaptive governance in parallel with adaptive vector behavior.

Environmental risk assessment frameworks (Peterson, 2025) highlight trade-offs in pest management, particularly regarding ecological toxicity and resistance evolution. Gene drive technologies represent a frontier intervention. Abram et al. (2026) outline environmental safety considerations for post-release monitoring of gene drive-modified mosquitoes. The success of such technologies depends on anticipating behavioral and ecological adaptation, including potential changes in mating patterns, dispersal behavior, or ecological niche occupation. Comparative vector ecology also informs adaptive analysis. Leal et al. (2024) document the distribution of Anopheles arabiensis in Cabo Verde, illustrating how geographic expansion interacts with local ecological conditions. Bezerra-Santos et al. (2026) provide analogous insights from sand fly ecology, reinforcing that vector management must account for species-specific behavioral complexity.

Ultimately, mosquito decision-making and adaptation to control measures reflect a co-evolutionary contest. Genetic resistance, behavioral avoidance, phenotypic plasticity, and ecological opportunism collectively undermine static intervention models. The relative paucity of comparative research between Anopheles and Culex in cognitive and behavioral domains represents a critical gap. Differences in feeding ecology, habitat preference, and sensory specialization likely translate into distinct adaptive strategies, yet these remain insufficiently integrated into control design.

Limited Comparative Studies

While much has been learned about the behaviors of *Anopheles* mosquitoes, particularly in relation to malaria transmission, fewer studies have examined the cognitive abilities and adaptive behaviors of *Culex* mosquitoes, especially in the context of their role in transmitting other diseases like West Nile virus and dengue (Branda *et al*., 2024). There is a lack of comparative studies that directly assess how *Anopheles* and *Culex* mosquitoes differ in their ability to learn, adapt, and respond to environmental cues. This knowledge gap limits the development of effective control strategies that can target both mosquito genera simultaneously, a critical step in integrated vector management.

Need for More Targeted Vector Control Strategies

The increasing resistance of mosquitoes to conventional control methods, such as insecticides and environmental modifications, necessitates a shift towards more targeted, behavior-based control strategies. Understanding the specific cognitive and adaptive behaviors of *Anopheles* and *Culex* mosquitoes will be critical in designing interventions that exploit their sensory processing, learning, and memory. For example, identifying the sensory cues that drive host-seeking behavior in both mosquito genera could lead to the development of more effective attractants or repellents. Similarly, understanding how mosquitoes adapt to environmental pressures can inform the design of more durable control strategies, such as genetic modifications or novel behavioral interventions.

Biology and Ecological Distribution of Anopheles and Culex Mosquitoes

Life Cycle and Ecological Roles

The life cycle of mosquitoes, including both *Anopheles* and *Culex*, follows a similar pattern, consisting of four main stages: egg, larva, pupa, and adult. However, the ecological roles and specific habitat requirements vary between the two genera, influencing their distribution and behavior.

Egg Stage

Anopheles Mosquitoes: The eggs of *Anopheles* mosquitoes are typically laid individually on the surface of water. Unlike other mosquito species, *Anopheles* eggs are characterized by their unique shape, being boat-shaped with a floatation device on either side, allowing them to float on the water's surface. These eggs are laid in clean, stagnant water bodies, such as ponds, swamps, and slow-moving streams (Javed, 2021). The female *Anopheles* mosquito will only lay eggs in water that is free of pollutants, as the larvae require clean water to thrive.

Culex Mosquitoes

In contrast, *Culex* mosquitoes lay their eggs in clusters known as "rafts," which float on the surface of water. These rafts are usually laid in polluted or organic-rich water bodies, such as drains, cesspools, ditches, and sewage systems. *Culex* mosquitoes can lay their eggs in both stagnant and flowing water, but their preference leans toward water that contains high amounts of organic matter and decomposing vegetation, which provides food for the larvae (Singh, Akhtar, & Gupta, 2024).

Larvae Stage

Anopheles Mosquitoes**:** *Anopheles* larvae are aquatic and are typically found at the surface of clean, still water. They are characterized by their distinct position at the water surface, where they lie parallel to the water, filtering microorganisms for food. The larvae of *Anopheles* are particularly sensitive to water quality, and their development is best suited to unpolluted environments. They undergo four larval instars before transitioning into the pupal stage. The larvae of *Anopheles* mosquitoes are particularly vulnerable to chemical pollutants and are less likely to survive in water that is contaminated with organic matter or chemicals.

Culex Mosquitoes

Culex larvae, unlike those of *Anopheles*, tend to live deeper in the water column and are less dependent on the quality of water. They have a more adaptable habitat preference and can survive in more polluted environments, such as wastewater, sewage, and polluted ditches. Like *Anopheles* larvae, *Culex* larvae pass through four instars, but they typically remain positioned at the surface in a more upright posture, where they feed on particulate matter, algae, and detritus (Naik et al., 2025). *Culex* larvae have a higher tolerance to organic pollution, making them more resilient in urban and industrial environments compared to *Anopheles*.

Pupal Stage

Anopheles Mosquitoes

The pupal stage in *Anopheles* mosquitoes is a non-feeding, resting stage, which lasts for 1-2 days before the adult emerges. Pupae of *Anopheles* mosquitoes are highly sensitive to disturbances and tend to remain near the surface, resting in an upright position. They are very sensitive to pollution, and their presence in a body of water can indicate relatively clean water.

Culex Mosquitoes

Similarly, *Culex* pupae also remain near the surface of the water, where they can respire through specialized structures called "breathing tubes." Unlike *Anopheles* pupae, however, *Culex* pupae are more tolerant of water pollution and can thrive in polluted water bodies that may be unsuitable for *Anopheles* larvae or pupae. The pupal stage typically lasts 1-3 days before the adult emerges.

Adult Stage

Anopheles Mosquitoes: Adult *Anopheles* mosquitoes are most commonly active during the night, although some species are also active during dusk and dawn. These mosquitoes are primarily known for their role in transmitting *Plasmodium* parasites, the causative agent of malaria. After mating, females seek a blood meal from a host, which is necessary for the development of their eggs. The adult *Anopheles* mosquito is most commonly found near water bodies, where they lay eggs. They are particularly attracted to warm, humid environments, and their presence is often a good indicator of nearby breeding sites.

Culex Mosquitoes

Adult *Culex* mosquitoes, like *Anopheles*, are primarily nocturnal. These mosquitoes are responsible for transmitting a range of viruses, including West Nile virus, and other pathogens like *Wuchereria bancrofti*, the

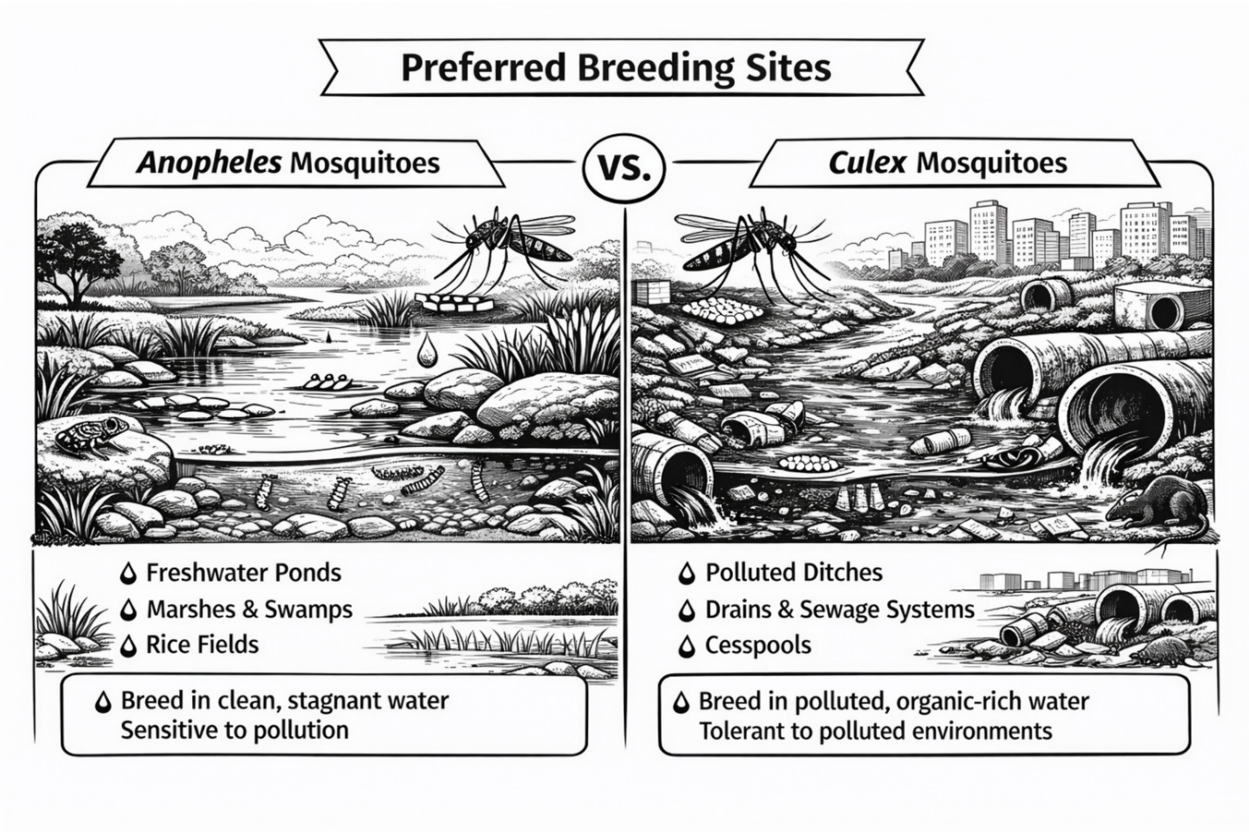

Figure 2: Preferred breeding sites of Anopheles vs Culex mosquitoes

causative agent of lymphatic filariasis. After mating, the female *Culex* seeks a blood meal and then lays her eggs in polluted or organically rich water sources. *Culex* mosquitoes can adapt to a variety of environments, and their tolerance for polluted habitats enables them to thrive in urban areas, where they are often found around sewage systems and stormwater drains (Tyagi *et al.*, 2025).

Preferred Breeding Sites

Anopheles Mosquitoes

Anopheles mosquitoes typically breed in clean, stagnant water. Their preferred breeding sites include freshwater ponds, marshes, swamps, rice fields, and slow-moving streams. These environments provide the clean water necessary for the survival of larvae and the development of pupae. The quality of the breeding site is crucial, as *Anopheles* mosquitoes are sensitive to pollutants and are less likely to breed in polluted water bodies. This preference for clean water limits the distribution of *Anopheles* mosquitoes to areas where clean water is abundant (Figure 2).

Culex Mosquitoes

Culex mosquitoes have a much broader range of breeding habitats. They are able to breed in both stagnant and flowing water, but they prefer areas with high organic matter, such as polluted ditches, drains, sewage systems, and cesspools (Figure 2). These habitats provide a rich source of food for *Culex* larvae, which feed on decaying organic matter. The ability of *Culex* mosquitoes to tolerate and thrive in polluted environments allows them to occupy a wider range of habitats, including urban and peri-urban areas (Branda et al., 2024).

Geographic Distribution

Global Distribution Patterns

Anopheles Mosquitoes: *Anopheles* mosquitoes are predominantly found in tropical and subtropical regions, with the highest abundance in sub-Saharan Africa, Southeast Asia, and parts of Latin America. The majority of malaria cases are reported in these regions, where *Anopheles* mosquitoes are the primary vectors of *Plasmodium* parasites. However, some species of *Anopheles* mosquitoes, such as *Anopheles stephensi*, have adapted to urban environments and are found in cities across Asia and Africa (Javed et al., 2021). These mosquitoes tend to thrive in areas where there are both water bodies for breeding and a high population of humans to provide blood meals. Culex Mosquitoes: *Culex* mosquitoes are found in a broader range of geographic areas, from tropical regions to temperate zones. These mosquitoes are widely distributed across North America, Europe, Asia, and Africa, particularly in areas with standing water, such as urban drainage systems. *Culex* mosquitoes are notably more adaptable to urban and human-modified environments, as they can breed in polluted water sources such as wastewater treatment facilities, septic tanks, and even rainwater runoff from urban areas. In addition to transmitting West Nile virus, *Culex* mosquitoes also play a role in the spread of lymphatic filariasis, particularly in tropical and subtropical regions (Tyagi *et al*., 2025).

Habitat Overlap and Differences in Environmental Preferences

While there is some overlap in the geographic ranges of *Anopheles* and *Culex* mosquitoes, their habitat preferences often differ significantly. *Anopheles* mosquitoes are typically found in rural and semi-rural areas, where clean, stagnant water bodies are common. They prefer to breed in natural water sources such as ponds, marshes, and wetlands. In contrast, *Culex* mosquitoes are more adaptable to human-altered environments and are commonly found in urban areas where they breed in polluted water sources like drains and sewers. This adaptability allows *Culex* mosquitoes to thrive in a wider range of environments, including areas with more urbanization and industrialization (González Pérez, 2023).

Environmental Adaptations

Tolerance to Varying Temperatures and Humidity

Anopheles Mosquitoes

Anopheles mosquitoes are sensitive to temperature and humidity, preferring warmer climates where temperatures range between 18-34°C. They are typically found in regions with high humidity, as these conditions help maintain the integrity of their eggs and larvae. *Anopheles* mosquitoes are most active in tropical and subtropical regions, although some species, such as *Anopheles stephensi*, have adapted to urban environments with warmer conditions.

Culex Mosquitoes

Culex mosquitoes are more tolerant of temperature fluctuations and humidity levels than *Anopheles*. They can be found in both temperate and tropical climates, with some species, such as *Culex pipiens*, being adapted to cooler, temperate regions. In contrast to *Anopheles*, *Culex* mosquitoes can survive in areas where environmental conditions vary more widely, including in urban environments with fluctuating temperatures and lower humidity levels (Naik et al., 2025).

Anopheles Preferences for Clean, Stagnant Water vs. Culex's Tolerance for Polluted Water

Anopheles Mosquitoes

The primary environmental preference of *Anopheles* mosquitoes is clean, stagnant water. These mosquitoes are highly sensitive to organic pollution, and their larvae do not thrive in polluted water (Figure 3). The clean water needed for the development of larvae and pupae often restricts the breeding range of *Anopheles* mosquitoes to areas with relatively little human activity and minimal industrial pollution (Singh *et al*., 2024).

Culex Mosquitoes

In contrast, *Culex* mosquitoes are more resilient and capable of surviving in polluted water environments (Figure 3). They are commonly found in urban and peri-urban environments, where they breed in sewage systems, polluted drains, and standing water contaminated with organic matter. *Culex* larvae feed on detritus, algae, and decomposing organic material, which makes polluted water sources suitable for their development (Tyagi et al., 2025).

Adaptive Behaviors: Comparative Analysis of ***Anopheles*** and ***Culex***

Feeding Behaviors

The feeding behaviors of *Anopheles* and *Culex* mosquitoes are central to their role as vectors of disease. Both genera feed on blood to obtain the necessary nutrients for egg development, but their blood-feeding strategies, preferences, and behaviors show key differences.

Blood-Feeding Preferences and Strategies

Anopheles Mosquitoes

Anopheles mosquitoes are notorious for being the primary vectors of *Plasmodium* parasites, the causative agents of malaria. Their blood-feeding strategy is critical for the transmission of this disease. Female *Anopheles* mosquitoes typically prefer to feed on human blood, especially in regions where human populations are abundant. This preference for humans, particularly in Africa, has made *Anopheles* mosquitoes the main culprit in malaria transmission (Javed, Bhatti, & Paradkar, 2021). They are also known to feed on other vertebrates, such as

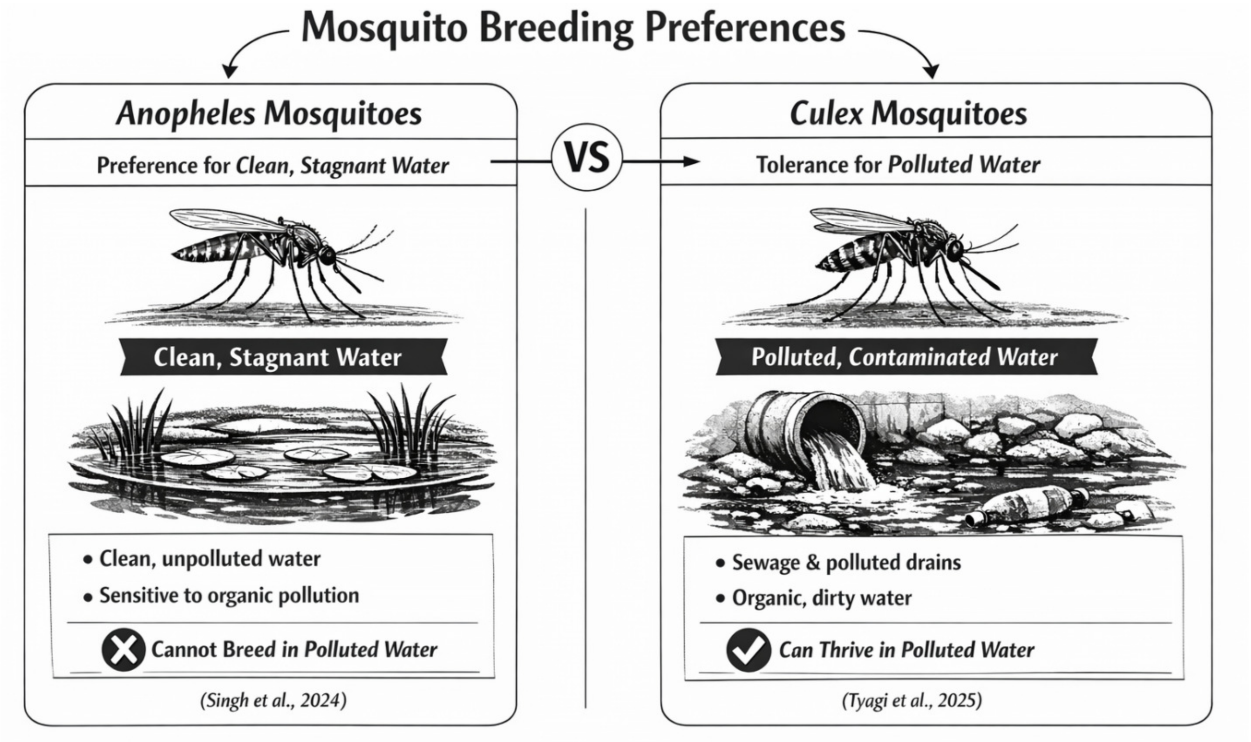

Figure 3: Breeding Water Preferences of Anopheles vs. Culex Mosquitoes

birds and livestock, depending on their geographical location and available hosts.

Feeding Frequency

Anopheles mosquitoes tend to feed infrequently but require a substantial blood meal to ensure successful egg development. They are often more selective in their feeding habits, and this selectivity can influence their behavior. For example, in areas where humans are not abundant, *Anopheles* mosquitoes may rely more heavily on non-human hosts. Additionally, *Anopheles* mosquitoes generally feed during the night, with some species being most active around dusk and dawn, while others feed throughout the night (Tyagi, Bhattacharya, & Naik, 2025).

Culex Mosquitoes

Culex mosquitoes, on the other hand, have a broader range of blood-feeding preferences. While they can feed on humans, they are equally opportunistic, feeding on a wide range of animals including birds, amphibians, and reptiles. This flexibility in host choice allows *Culex* mosquitoes to thrive in diverse environments, from rural areas to urban spaces where human populations are mixed with birds and other animals (Branda et al., 2024). *Culex* mosquitoes are also vectors for several viruses, including West Nile virus and the dengue virus, and their blood-feeding behavior plays a crucial role in the transmission of these pathogens.

Feeding Patterns

While both *Anopheles* and *Culex* mosquitoes primarily feed at night, *Culex* mosquitoes are more likely to bite during the late evening and early morning hours, with some species exhibiting a preference for evening feeding. The timing of feeding can vary with environmental factors, such as temperature and humidity, and local host availability. In contrast to *Anopheles*, *Culex* mosquitoes often exhibit less selectivity in host choice, feeding on both humans and animals in a variety of habitats, including urban and rural areas (Singh, Akhtar, & Gupta, 2024).

Differences in Biting Patterns (Time of Day, Host Preference, Feeding Duration)

Anopheles Mosquitoes

The biting behavior of *Anopheles* mosquitoes is highly influenced by the need for blood meals to support egg production. These mosquitoes tend to be more nocturnal, with most feeding activity occurring between dusk and dawn. The peak feeding times are often just after sunset and just before dawn when humans are most likely to be asleep. However, *Anopheles* mosquitoes, particularly those responsible for malaria transmission, can be more aggressive in areas where human populations are dense, contributing to higher transmission rates (Naik et al., 2025).

Host Preference

Anopheles mosquitoes, particularly *Anopheles gambiae*, show a strong preference for human blood, which may be linked to their evolutionary history as human malaria vectors. However, in areas where humans are less abundant, these mosquitoes will feed on other vertebrates such as livestock and birds. Some *Anopheles* species, like *Anopheles stephensi*, have adapted to urban environments, where they feed on both humans and animals (González Pérez, 2023).

Feeding Duration

The feeding duration of *Anopheles* mosquitoes is typically longer compared to *Culex* mosquitoes. *Anopheles* mosquitoes need a substantial blood meal to support their egg production, which results in prolonged feeding times, often up to 10 minutes or longer, depending on the host and environmental conditions.

Culex Mosquitoes

The feeding behavior of *Culex* mosquitoes is more flexible and less specific compared to *Anopheles* mosquitoes. *Culex* mosquitoes are also nocturnal, but they are more opportunistic in their feeding habits and may bite throughout the night, from dusk until dawn. Some species may also feed during the day, particularly in areas where hosts are readily available.

Host Preference

Culex mosquitoes are known to feed on a broader range of hosts, including birds, amphibians, and humans. Their preference for birds makes them important vectors for West Nile virus, as birds act as reservoirs for the virus. However, in urban environments, *Culex* mosquitoes will readily feed on human hosts, especially in areas with high human-animal interactions (Branda et al., 2024).

Feeding Duration

Culex mosquitoes tend to have shorter feeding durations compared to *Anopheles* mosquitoes, typically feeding for only a few minutes. This shorter feeding period is partly due to the lower volume of blood required for egg development in *Culex* mosquitoes, which results in quicker blood meal intake.

Host Seeking and Avoidance

Host seeking is a critical behavior for both *Anopheles* and *Culex* mosquitoes, as it determines their ability to find a suitable blood meal. These mosquitoes use a variety of environmental and sensory cues to locate hosts.

Host Attraction Mechanisms

Anopheles Mosquitoes

Anopheles mosquitoes rely on several cues to locate their hosts, including carbon dioxide (CO_2), body odors, heat, and visual stimuli. CO_2 is one of the most important signals for *Anopheles* mosquitoes, as it is emitted by all vertebrate hosts during respiration. *Anopheles* mosquitoes are also attracted to the body odors of humans and animals, particularly lactic acid, which is produced by sweat. The heat emitted by a host's body also acts as an important attractant, particularly for *Anopheles gambiae*, which is known for its strong response to thermal cues (Naik et al., 2025).

Culex Mosquitoes

Similarly, *Culex* mosquitoes are attracted to CO2, body odors, and heat. However, *Culex* mosquitoes are also more sensitive to ammonia and other volatile compounds found in sweat, which may make them more likely to bite certain animal hosts, such as birds, in addition to humans (Singh et al., 2024). In urban areas, *Culex* mosquitoes are attracted to the smell of organic waste in polluted environments, which also helps guide them to potential blood meal sources, such as animals and humans near waste sources.

Avoidance Behaviors

Anopheles Mosquitoes

Anopheles mosquitoes are generally attracted to humans and will actively seek them out. However, they also exhibit avoidance behaviors in response to environmental cues such as light and movement. For example, they are less likely to feed in brightly lit areas and prefer areas with low light levels. Additionally, *Anopheles* mosquitoes exhibit avoidance behavior in response to repellents, such as DEET (N, N-diethyl-meta-toluamide), which can deter mosquitoes from approaching humans (Javed et al., 2021).

Culex Mosquitoes

Culex mosquitoes also exhibit avoidance behaviors, particularly in response to certain environmental conditions. They tend to avoid bright light and may be deterred by chemical repellents, although they are generally more tolerant of human presence compared to *Anopheles* mosquitoes. *Culex* mosquitoes also avoid areas with high levels of insecticides, and some species exhibit avoidance behaviors in response to sprays or treated surfaces, which can make control measures less effective in the long term (Tyagi et al., 2025).

Mating Behaviors

Mating is a crucial process in the reproductive cycle of mosquitoes. Both *Anopheles* and *Culex* mosquitoes exhibit distinct mating behaviors, which can influence their population dynamics and the effectiveness of vector control efforts.
Courtship and Mating Rituals

Anopheles Mosquitoes

Mating in *Anopheles* mosquitoes typically occurs in flight, where males actively seek females. Males are attracted to the sound produced by the female's wing beats, a behavior known as "mating swarms," where males congregate in specific areas to attract females. Once a male has found a female, he will engage in a mating dance, where he tries to align with the female and copulate. This behavior plays a crucial role in the mating success of *Anopheles* mosquitoes, as the males must be able to detect the female's mating calls (Naik et al., 2025).

Culex Mosquitoes

Culex mosquitoes also exhibit mating swarms, but the behavior is more pronounced in some species, particularly in urban environments. The males of *Culex* mosquitoes often form large swarms in open areas and emit mating sounds to attract females. Mating occurs when a female enters the swarm, and the male attempts to copulate in flight. Unlike *Anopheles* mosquitoes, *Culex* mosquitoes can mate at any time of day, but they tend to prefer twilight hours for mating (Singh, Akhtar, & Gupta, 2024).

Male-Female Interactions and Implications for Population Control

Mating behaviors are crucial to understanding how mosquito populations thrive or fail. In *Anopheles* mosquitoes, where mating success depends on the male’s ability to detect the female and engage in copulation, population control strategies such as the release of sterilized males (sterile insect technique) or genetic modification strategies (e.g., gene drive technology) can interfere with the normal mating process, leading to reduced reproductive success (Branda et al., 2024). Similarly, in *Culex* mosquitoes, male-female interactions and mating swarms can be disrupted by pheromone traps or environmental manipulations, contributing to vector control efforts (Tyagi et al., 2025).

Survival Strategies and Resilience

Both *Anopheles* and *Culex* mosquitoes exhibit impressive survival strategies that enhance their resilience to environmental pressures.

Resistance to Environmental Stress

Anopheles Mosquitoes

Anopheles mosquitoes are sensitive to temperature extremes and desiccation. Most species prefer humid environments and are less likely to survive in dry conditions. However, some species, such as *Anopheles stephensi*, have adapted to urban environments, showing greater tolerance to temperature fluctuations and desiccation (Naik et al., 2025). These adaptations allow them to persist in harsh conditions and continue to transmit malaria.

Culex Mosquitoes

Culex mosquitoes are generally more resilient to environmental stress than *Anopheles*. They are capable of surviving in a broader range of temperatures and humidity levels and are better equipped to endure fluctuating environmental conditions. *Culex* mosquitoes can also survive in polluted water, which provides them with a unique ecological niche compared to *Anopheles* mosquitoes (Singh et al., 2024).

Immunity to Insecticides and Adaptive Resistance Mechanisms

Anopheles Mosquitoes

The rise of insecticide resistance in *Anopheles* mosquitoes has become a significant challenge in malaria control. Resistance to common insecticides, such as pyrethroids, has been documented in various *Anopheles* species, particularly in regions with widespread use of insecticide-treated nets and indoor residual sprays. These mosquitoes have evolved genetic mutations that confer resistance, making it more difficult to control their populations (Tyagi et al., 2025).

Culex Mosquitoes

Similarly, *Culex* mosquitoes have developed resistance to insecticides used for vector control. The evolution of resistance in *Culex* mosquitoes is often driven by the extensive use of insecticides in urban environments, where these mosquitoes thrive. Some *Culex* species, such as *Culex pipiens*, have developed resistance to pyrethroids and other classes of insecticides, making control efforts less effective in some regions (Naik et al., 2025).

Behavioral Adaptations to Vector Control Measures

Behavioral Resistance to Insecticide-Treated Nets, IRS, and Larvicides

Both *Anopheles* and *Culex* mosquitoes have evolved behavioral resistance to vector control measures, which can significantly reduce the effectiveness of these interventions.

Anopheles Mosquitoes

Anopheles mosquitoes, particularly in areas where insecticide-treated nets (ITNs) are widely used, have exhibited behavioral resistance. Some mosquitoes avoid feeding on humans sleeping under nets, feeding at times when the nets are less likely to be effective (e.g., during the day or at times when people are less active). Additionally, *Anopheles* mosquitoes have been observed to fly higher or lower than usual to avoid contact with treated surfaces (Tyagi et al., 2025).

Culex Mosquitoes

Culex mosquitoes also exhibit behavioral resistance to control measures. In areas with extensive use of IRS and larvicides, *Culex* mosquitoes have been shown to alter their feeding and breeding behaviors. They may seek alternative habitats for oviposition or change their feeding times to avoid periods when control measures are most active (Branda et al., 2024).

Evolution of "Behavioral Resistance" in Response to Common Control Methods

The concept of "behavioral resistance" refers to the changes in mosquito behavior that make them less susceptible to control measures. Both *Anopheles* and *Culex* mosquitoes have demonstrated this form of resistance in response to the widespread use of insecticides and other control measures. As mosquitoes evolve to avoid control measures, vector control programs must adapt by developing new strategies, such as combining chemical, biological, and behavioral approaches to achieve sustainable control (Naik et al., 2025).

Intelligence and Cognitive Abilities in Mosquitoes

The cognitive abilities of mosquitoes, particularly their sensory systems, learning, memory, and decision-making, play a crucial role in their survival and vector competence. Understanding these processes is essential for developing more targeted and effective mosquito control strategies, as well as improving surveillance techniques. Both *Anopheles* and *Culex* mosquitoes exhibit remarkable intelligence, enabling them to navigate their environment, locate hosts for blood meals, avoid threats, and reproduce successfully. This section explores the sensory modalities, learning and memory mechanisms, and decision-making processes in mosquitoes, focusing on how these abilities help them adapt to their environment and optimize their behaviors.

Sensory Systems

Mosquitoes possess an array of sophisticated sensory systems that allow them to detect various environmental cues essential for survival. These cues help mosquitoes locate hosts, find breeding sites, and navigate through complex environments. The primary sensory modalities used by mosquitoes include olfaction, vision, thermoreception, and mechanoreception. Each of these sensory systems plays a crucial role in different aspects of mosquito behavior, including host-seeking, mating, and environmental adaptation.

Olfaction (Smell)

Olfaction is one of the most critical sensory systems for mosquitoes, especially for host location and navigation. Mosquitoes rely heavily on chemical signals to detect potential hosts, locate breeding sites, and find mates. The olfactory system of mosquitoes is highly developed, allowing them to detect a wide range of odors emitted by hosts and the environment.

Host Location

Anopheles and *Culex* mosquitoes are particularly sensitive to carbon dioxide (CO2), which is released by all vertebrates during respiration. This chemical cue serves as a primary attractant for mosquitoes, guiding them towards potential hosts. Additionally, mosquitoes can detect specific body odors, such as lactic acid, ammonia, and other volatile compounds found in sweat, which play a significant role in attracting them to humans and animals (Singh et al., 2024). For example, *Anopheles gambiae* is highly attracted to the body odor of humans, with lactic acid being one of the key compounds that influence this attraction.

Breeding Site Location

Olfactory cues also help mosquitoes locate suitable breeding sites. *Anopheles* mosquitoes prefer clean, stagnant water, while *Culex* mosquitoes are attracted to polluted, organic-rich water sources. The ability of mosquitoes to distinguish between different water types based on olfactory cues helps them choose the most appropriate site for egg laying (Naik et al., 2025).

Vision (Sight)

Although mosquitoes rely less on vision compared to other sensory modalities, vision still plays an important role in their behavior, particularly in close-range host detection and navigation in certain environments.

Host Attraction

Both *Anopheles* and *Culex* mosquitoes can detect visual cues from a distance, such as movement and body size, which help them identify potential hosts. Mosquitoes are more likely to be attracted to larger objects that move, such as humans and animals. They are also sensitive to contrasts in light and dark, which help them navigate toward their target in low-light conditions (González Pérez, 2023). Some species, like *Anopheles stephensi*, have adapted to urban environments where they rely more on visual cues to locate human hosts in artificial light conditions.

Mating

Visual cues are also important for mating behavior. *Culex* mosquitoes, for example, use visual stimuli to locate mating swarms where males aggregate and produce mating calls. In *Anopheles* mosquitoes, males are attracted to the wing beat frequencies of females, which can be perceived visually and through auditory cues (Branda et al., 2024).

Thermoreception (Heat)

Thermoreception allows mosquitoes to detect temperature variations, which is crucial for locating warm-blooded hosts and avoiding environmental extremes. Both *Anopheles* and *Culex* mosquitoes are highly sensitive to thermal cues, which they use to guide their movements.

Host Location

Warm-blooded animals, including humans, emit heat that mosquitoes can detect through specialized receptors located on their antennae and maxillary palps. *Anopheles* mosquitoes, in particular, are highly sensitive to the thermal gradient produced by the human body, which helps guide them toward their hosts, especially in conditions where CO_2 detection alone may not be sufficient (Naik et al., 2025). Heat detection is a crucial mechanism for mosquitoes to locate hosts in both outdoor and indoor environments.

Environmental Adaptation

Mosquitoes also use thermoreception to adapt to temperature extremes. Many species of *Anopheles* and *Culex* mosquitoes are capable of detecting subtle temperature changes in their environment, which allows them to avoid unsuitable habitats and seek more favorable conditions for survival and reproduction (Singh et al., 2024).

Mechanoreception (Touch)

Mechanoreception refers to the ability of mosquitoes to detect mechanical forces such as vibrations, air currents, and surface contact. This sensory modality is particularly important for host location, navigation, and mating.

Host Detection

Mosquitoes use mechanoreception to detect the subtle movements of potential hosts. For example, the slightest motion, such as the movement of a human or animal, can trigger a response from mosquitoes, guiding them toward their target. Mosquitoes are also sensitive to air currents caused by human movement or respiration, which they use to home in on hosts (Tyagi et al., 2025).

Mating Behavior

During mating, *Anopheles* and *Culex* mosquitoes use mechanoreception to detect the wing beat frequencies of potential mates. Males can detect the vibrations produced by females' wing beats, which are critical for locating females during mating swarms.

Learning and Memory

Learning and memory are important cognitive abilities that allow mosquitoes to adapt to environmental changes and optimize their behaviors. Evidence suggests that mosquitoes are capable of associative learning, conditioned responses, and memory retention, which help them adapt to changing conditions, such as variations in host availability or environmental cues.

Evidence of Associative Learning and Conditioned Responses

Conditioned Learning

Mosquitoes can learn to associate specific environmental cues with the availability of blood meals. Studies have shown that both *Anopheles* and *Culex* mosquitoes can associate certain odors or environmental conditions with the presence of a host, enabling them to optimize their host-seeking behavior over time. For example, if a mosquito feeds on a host that produces a particular scent or heat signature, it may learn to associate those cues with a successful blood meal, increasing its chances of locating a host in the future (González Pérez, 2023).

Behavioral Conditioning

In laboratory studies, mosquitoes have been conditioned to respond to specific stimuli. *Anopheles* mosquitoes, for instance, can be trained to associate a specific odor with a blood meal, leading them to preferentially seek out that odor in subsequent trials. Similarly, *Culex* mosquitoes have demonstrated the ability to learn and remember specific smells or temperature gradients associated with favorable conditions for oviposition and host location (Tyagi et al., 2025).

Memory Retention and Adaptive Behavior

Memory Retention

Mosquitoes possess short-term and long-term memory, which allows them to retain information over time. Short-term memory is important for immediate decisions, such as recognizing environmental cues that lead to a successful blood meal or identifying safe places for egg-laying. Long-term memory enables mosquitoes to remember environmental patterns, such as the availability of hosts or breeding sites, over extended periods. This type of memory is particularly useful for mosquitoes that need to find suitable breeding sites in fluctuating environmental conditions (Naik et al., 2025).

Environmental Adaptation

The memory retention abilities of mosquitoes allow them to adapt to changes in their environment. For example, if a mosquito encounters a repellent or learns that a certain host is not suitable, it may avoid that host or location in the future. This cognitive flexibility helps mosquitoes optimize their survival strategies and enhances their resilience in the face of changing environmental conditions (Singh et al., 2024).

Decision-Making Processes

Mosquitoes exhibit complex decision-making processes that are essential for host selection, mating, and reproductive success. These processes are influenced by a combination of sensory inputs, learned experiences, and environmental cues, which guide their actions in ways that maximize their chances of survival and reproduction.

Mechanisms of Host Selection

Host Preference

The selection of a host for blood feeding is influenced by several factors, including the mosquito's sensory abilities, previous experiences, and environmental conditions. Both *Anopheles* and *Culex* mosquitoes use a combination of CO_2 detection, body odor, heat, and visual cues to choose their hosts. However, *Anopheles* mosquitoes tend to prefer human hosts, especially in areas where humans are abundant, while *Culex* mosquitoes are more opportunistic and will feed on a variety of animals, including birds, amphibians, and humans (Branda et al., 2024).

Behavioral Plasticity

Mosquitoes exhibit significant behavioral plasticity, allowing them to switch between strategies depending on environmental conditions. For example, *Anopheles* mosquitoes may prefer human hosts in regions with high human density but will feed on other vertebrates in areas with fewer humans. Similarly, *Culex* mosquitoes may shift between feeding on humans and animals depending on the availability of hosts and the surrounding environmental cues (Javed, Bhatti, & Paradkar, 2021).

Behavioral Plasticity: Host Selection and Oviposition

Blood Meal Choice

Both *Anopheles* and *Culex* mosquitoes demonstrate flexibility in choosing their blood meal source based on environmental factors such as host availability, feeding competition, and host odor. When a preferred host is not available, mosquitoes may adjust their strategy and feed on alternative hosts, including birds, reptiles, or livestock. This behavioral plasticity helps ensure that mosquitoes are able to meet their nutritional needs in different environmental conditions (Naik et al., 2025).

Oviposition Site Selection

Mosquitoes also exhibit behavioral plasticity when selecting oviposition sites. *Anopheles* mosquitoes prefer clean, stagnant water for egg-laying, while *Culex* mosquitoes are more adaptable and can breed in a variety of water sources, including polluted environments. However, both genera will adapt their oviposition behavior based on environmental cues, such as the presence of competitors, the availability of suitable breeding sites, and the presence of predators (Tyagi et al., 2025). The intelligence and cognitive abilities of mosquitoes are fundamental to their success as disease vectors. Through complex sensory systems, learning, memory, and decision-making, mosquitoes are able to navigate their environments, locate hosts for blood meals, and select appropriate breeding sites (Figure 4). Understanding these cognitive processes can lead to the development of more effective vector control strategies, such as exploiting mosquitoes' sensory preferences or disrupting their learning and memory. As the challenges of mosquito-

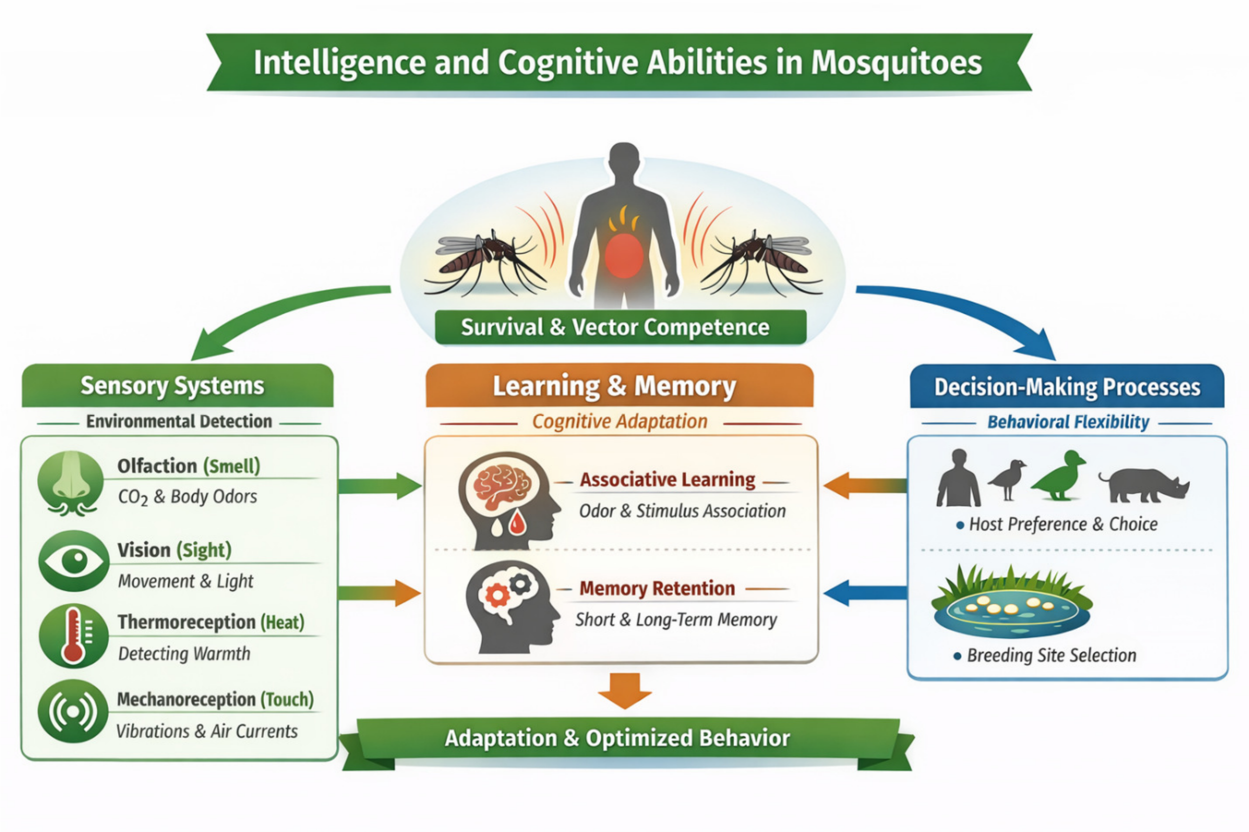

Figure 4: Intelligence and Cognitive Abilities in Mosquitoes

borne diseases persist, gaining a deeper understanding of mosquito cognition will be crucial in developing innovative, sustainable solutions for reducing the transmission of diseases like malaria, dengue, and West Nile virus.

Implications for Surveillance and Monitoring

Surveillance and monitoring constitute the epistemic backbone of vector control, transforming entomological observations into actionable public health intelligence. For disease vectors such as *Anopheles* and *Culex*, surveillance extends beyond population enumeration to encompass behavioral plasticity, host preference dynamics, ecological adaptation, and resistance development. As vector-borne diseases expand under pressures of climate variability and urbanization, surveillance systems must evolve from static abundance-based assessments to behaviorally informed and predictive frameworks.

Current Surveillance Methods

Trap-Based Sampling

Trap-based sampling remains central to mosquito surveillance programs. CDC light traps, which combine light and CO_2 as attractants, are widely deployed to monitor nocturnal species including *Anopheles* and *Culex* (Tyagi et al., 2025). By simulating vertebrate respiration and exploiting phototactic responses, these traps generate standardized abundance estimates across ecological settings. BG-Sentinel traps extend this principle by incorporating lactic acid and synthetic odor blends to mimic human scent profiles, improving detection of anthropophilic mosquitoes (Javed, Bhatti, & Paradkar, 2021). Although initially designed for *Aedes*, they are increasingly used to capture other genera.Gravid traps specifically target ovipositing females, often using fermented organic infusions to attract *Culex* species seeking egg-laying sites (Naik et al., 2025). These traps provide insights into reproductive activity and local breeding intensity. While effective for population monitoring and species identification, trap-based systems assume relatively stable behavioral responses to attractants an assumption increasingly challenged by evidence of behavioral adaptation.

Human Landing Catches

Human landing catches (HLCs) directly measure host-seeking and biting behavior by collecting mosquitoes as they land on exposed human skin. This approach is particularly informative for assessing *Anopheles* biting rates and malaria transmission dynamics. The primary advantage of HLCs lies in their ecological validity: they measure actual human-vector contact and capture fine-scale temporal patterns of feeding activity. However, ethical concerns and exposure risks limit their scalability. Moreover, HLCs may underrepresent zoophilic or opportunistic feeders, particularly among *Culex* populations (Tyagi et al., 2025).

Ovitraps

Ovitraps provide non-invasive monitoring of egg-laying behavior, especially for container-breeding species. By offering artificial oviposition substrates, they estimate reproductive activity and local population trends (Singh et al., 2024). However, ovitraps are less suitable for *Anopheles*, which prefer natural water bodies. Furthermore, they yield limited behavioral information beyond oviposition patterns and do not capture host-seeking or feeding dynamics.

Limitations of Current Surveillance Methods

Limited Species Detection

Traditional methods may inadequately detect species exhibiting divergent host preferences or feeding strategies. Anthropophilic *Anopheles* may be overrepresented in human-centered surveillance, while opportunistic *Culex* species may be underestimated (Tyagi et al., 2025). This introduces sampling bias that can distort epidemiological risk assessment.

Behavioral Resistance to Traps and Repellents

Beyond physiological insecticide resistance, mosquitoes display behavioral resistance altered feeding times, increased exophily, or avoidance of treated surfaces (Singh et al., 2024). Populations repeatedly exposed to specific trap cues or repellents may learn to avoid them, reducing surveillance sensitivity and masking true abundance.

Environmental Factors

Temperature, humidity, rainfall, and microhabitat variability significantly influence mosquito activity and responsiveness to attractants. Fluctuating environmental conditions may reduce trap efficacy independent of actual population changes (Naik et al., 2025). Without integrating ecological covariates, surveillance systems risk conflating environmental noise with epidemiologically meaningful trends.

Behavioral and Cognitive Considerations for Surveillance

Improving Trapping Methods

Mosquito host-seeking involves multisensory integration of CO_2, volatile compounds, heat, and visual contrasts. Refining traps to replicate ecologically realistic cue combinations can enhance capture efficiency (Javed et al., 2021). Targeted attractant blends such as ammonia or fermentation volatiles can increase species-specific sensitivity (Naik et al., 2025). Aligning trap deployment with peak circadian activity (e.g., nocturnal *Anopheles*, crepuscular *Culex*) further optimizes surveillance accuracy (Branda et al., 2024).

Adaptive Behaviors Impacting Detection

Learning-mediated avoidance and habituation to chemical cues may reduce trap effectiveness over time. Incorporating novel attractants or rotating cue profiles may mitigate behavioral desensitization (Tyagi et al., 2025). Surveillance systems must therefore be adaptive rather than static, anticipating evolutionary and cognitive shifts.

Innovative Surveillance Strategies

Use of Olfactometers and Behavioral Assays

Olfactometers allow controlled measurement of mosquito attraction and aversion to specific odors. These laboratory-based systems elucidate olfactory preference hierarchies and learning responses (Naik et al., 2025). Translating such findings into field-adapted attractant systems strengthens ecological validity. Behavioral assays also quantify responses to environmental variables, enabling refinement of trap designs and identification of emerging avoidance behaviors (Singh et al., 2024).

Integration of Behavioral Data into Predictive Models

Incorporating behavioral parameters host preference plasticity, biting time shifts, oviposition site selection into predictive models enhances outbreak forecasting (Tyagi et al., 2025). Real-time integration of entomological and environmental data enables dynamic risk mapping and targeted intervention deployment (Branda et al., 2024).

Vector Control Strategies: A Behavioral Perspective

Vector control remains central to disease prevention. However, integrating behavioral insight into conventional and innovative control strategies enhances sustainability and long-term effectiveness.

Conventional Vector Control Methods

Insecticide-Based Control: Mechanisms, Effectiveness, and Challenges

Pyrethroids and organophosphates disrupt neural signaling pathways in mosquitoes, forming the foundation of indoor residual spraying (IRS) and insecticide-treated nets (ITNs) (Tyagi et al., 2025). Although effective in reducing malaria transmission, resistance both physiological and behavioral undermines long-term impact (Naik et al., 2025). Behavioral shifts, including altered feeding times or increased outdoor biting, represent adaptive responses that complicate surveillance and intervention efficacy.

Biological Control: The Role of Natural Predators and Pathogens

Biological agents such as larvivorous fish and microbial pathogens (e.g., *Bacillus thuringiensis israelensis*) offer environmentally sustainable alternatives (Singh et al., 2024). However, ecological variability and slower population impact limit standalone effectiveness.

Innovative Vector Control Strategies

Genetic Modification: Genetically Modified Mosquitoes, Sterile Insect Technique, and Gene-Drive Technologies

Genetic approaches aim to suppress populations or reduce vector competence. Self-limiting genetically modified mosquitoes and sterile insect techniques have demonstrated population reductions in field trials (Singh et al., 2024). Gene-drive technologies accelerate the spread of beneficial genetic traits, such as malaria resistance (Branda et al., 2024). Continuous behavioral surveillance is essential to detect compensatory adaptations affecting mating, dispersal, or feeding.

Behavioral Control: Altering Mosquito Behavior through Chemosensory Manipulation

Pheromones, repellents, and synthetic attractants manipulate mosquito sensory systems to disrupt mating and feeding (Javed et al., 2021). Novel formulations targeting behavioral pathways may overcome resistance to traditional repellents (Tyagi et al., 2025).

Case Studies: Review of Successful Behavioral-Based Strategies

Field trials involving genetically engineered mosquitoes have achieved substantial reductions in wild populations, demonstrating proof-of-concept for population suppression strategies (Singh et al., 2024). Sterile insect releases targeting *Culex* have reduced West Nile virus transmission in selected regions (Naik et al., 2025). Pheromone-based mating disruption has also shown promise in *Anopheles* control (Javed et al., 2021).

Challenges in Implementation of Behavior-Based Control

Ecological and Environmental Challenges

Seasonal variability and microenvironmental heterogeneity influence behavioral responses to control measures (Tyagi et al., 2025). Non-target species effects, ecological disruption, and potential resistance development remain significant concerns (Branda et al., 2024; Singh et al., 2024).

Technological and Operational Limitations

Mass production of genetically modified mosquitoes, advanced behavioral assays, and real-time surveillance infrastructure require substantial technical capacity (Javed et al., 2021). Resource-limited settings may face implementation barriers. Public perception and ethical concerns surrounding genetic modification further complicate large-scale adoption (Tyagi et al., 2025).

Integration with Existing Control Measures

Behavior-based strategies must operate synergistically with conventional tools such as ITNs and larvicides (Singh et al., 2024). Robust behavioral surveillance is critical for assessing long-term effectiveness and guiding adaptive management (Branda et al., 2024).

Future Directions in Mosquito Behavioral Research

Advances in Neuroethology: Understanding Mosquito Brain Function and Behavior

Neuroethological research reveals complex sensory integration mechanisms underlying host detection and mating behavior. Targeting neural pathways may enable highly specific behavioral disruption strategies (Naik et al., 2025).

Interdisciplinary Approaches

Collaborative research integrating entomology, genetics, ecology, and behavioral science strengthens translational impact and policy alignment (Singh et al., 2024).

Personalized Vector Control

Tailoring interventions to local ecological and behavioral contexts enhances efficiency and reduces non-target impacts. Personalized vector control aligns surveillance, behavioral data, and environmental variability to optimize public health outcomes (Naik et al., 2025).

Conclusion

In conclusion, understanding mosquito intelligence and behavioral adaptations is critical for improving vector control strategies. Both *Anopheles* and *Culex* mosquitoes exhibit remarkable cognitive abilities, including complex sensory systems, learning, and decision-making, which influence their interactions with humans and their environment. Behavior-based control methods, including genetic modifications, pheromone manipulation, and chemosensory disruption, offer promising alternatives to traditional insecticide-based strategies. However, the implementation of these methods faces several challenges, including ecological, technological, and ethical concerns. Moving forward, interdisciplinary research and personalized vector control approaches will be essential to overcome these challenges and develop more sustainable and effective mosquito control strategies.

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