Behavioral Ecology of Adult *Anopheles gambiae*: Insights for Malaria Control in Sub-Saharan Africa

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Received 15/10/2025 Revised 09/11/2025 Accepted 12/16/2025

Abstract

Background: Malaria remains a significant challenge to public health and socio-economic development in Sub-Saharan Africa, primarily transmitted by the vector *Anopheles gambiae*.

Objective: This review aims to examine the behavioural ecology of *A. gambiae* and synthesize the implications for current and future malaria control strategies.

Methods: A comprehensive literature review was conducted, focusing on the factors influencing the vectorial capacity of *A. gambiae* and the integrated approaches for its control.

Results: The efficiency of *A. gambiae* as a vector is driven by its nocturnal, anthropophilic feeding habits and remarkable environmental adaptability. Key anthropogenic and ecological factors, including urbanisation and climate change, are shifting mosquito habitats and influencing critical behaviours. Furthermore, evolving metabolic resistance compromises conventional chemical control. The impact of malaria is multifaceted, encompassing severe health outcomes and significant economic burdens. Emerging technologies like CRISPR-based gene drives, *Wolbachia* biocontrol, and the R21/MM vaccine offer promising solutions. Sustainable success is contingent on integrating these with community-driven interventions like larval source management within a holistic One Health approach.

Conclusion: Eradicating malaria in Sub-Saharan Africa is an attainable yet formidable goal. Future efforts must prioritize rigorous field testing of novel tools and generate predictive models through interdisciplinary research that integrates behavioural, ecological, and socioeconomic data. This requires adaptive, evidence-based strategies and enhanced surveillance systems.

Keywords: *Anopheles gambiae*, Feeding, Resting, Malaria Transmission Dynamics, Malaria Control

Introduction

Malaria is one of the significant challenges for public health and socio-economic development in Sub-Saharan Africa, with *Anopheles gambiae* being the primary vector, significantly contributing to the region's high malaria incidence (1, 2). The *A. gambiae* mosquito exhibits anthropophilic and endophilic behavior because it frequently feeds on humans while preferring to bite indoors during nighttime (3, 4). The short reproductive cycle of this mosquito species enables fast population growth, which maintains high transmission rates for extended periods (5). The capacity of this mosquito species to thrive in diverse environments enhances its effectiveness in spreading *Plasmodium* parasites that cause malaria (6, 7). The combination of these traits enables fast disease transmission and presents obstacles to traditional vector management approaches. World Health Organization (WHO) data revea3 that the African region experiences 94% of worldwide malaria cases and 95% of malaria deaths, indicating an urgent requirement to develop new behavior-focused mosquito control methods (8).

New research findings have expanded knowledge regarding *A. gambiae* behaviors and their impact on malaria transmission dynamics. Environmental conditions such as temperature and humidity strongly influence feeding behavior and host-seeking activity in *A. gambiae*, which impacts its ability to transmit malaria. The effectiveness of *A. gambiae* as a malaria vector depends directly on its feeding patterns and host-seeking behaviors (9). Urbanization modifies *A. gambiae* habitat preferences, which increases human contact frequency in cities and raises malaria transmission risks (10). According to Armando et al. (2023), malaria cases were mainly affected by socio-economic elements and climatic conditions like temperature and rainfall. These findings underscore the necessity of integrating ecological and socio-economic variables with climate data into malaria control strategies to improve their functionality across different environments throughout Sub-Saharan Africa (11).

In Sub-Saharan Africa, malaria transmission is primarily driven by several mosquito species belonging to the *Anopheles gambiae* complex and the *Anopheles funestus* group. The dominant vectors include *Anopheles gambiae sensu stricto*, *An. arabiensis*, *An. Coluzzii*, and *An. Funestus* with considerable spatial and ecological variation in its distribution and behavior. Among these, *A. gambiae s.s.* is regarded as the most efficient malaria vector because of its strong anthropophilic and endophilic behavior, high vectorial capacity, and remarkable adaptability to changing environmental conditions. These biological and ecological characteristics make *A. gambiae* the principal malaria vector across much of tropical Africa and justify its selection as the focus of this review (12-15).

Significant advancement has been made in the behavioral ecology of *A. gambiae*, but critical constraints and understudied issues remain. Foremost among these is the inexcusable absence, especially in urban centers, of systematic data on the rate of environmental and socio-economic changes that have a bearing on mosquito behavior and the epidemiologic dynamics of malaria (10). Moreover, although genetic and environmental management techniques exhibit potential, their long-term effectiveness and scalability are still predominantly unexamined, particularly in varied ecological settings. The integration of behavioral data with climate and socio-economic models remains limited, which hinders the development of predictive tools for malaria control. (16). This review addresses these gaps by considering the influences of environmental factors on *A. gambiae* behavior and identifying how this knowledge can be exploited for better malaria control in Sub-Saharan Africa.

Main Malaria Carriers in Sub-Saharan Africa

In Sub-Saharan Africa, the transmission of malaria is mainly facilitated by various mosquito species from the Anopheles gambiae complex and the Anopheles funestus group. The key vectors include Anopheles gambiae sensu stricto, An. arabiensis, An. Coluzzii, and An. Funestus, which exhibits significant spatial and ecological differences in its distribution and behavior. Among these species, A. gambiae s.s. is considered the most effective malaria vector due to its strong preference for humans and its tendency to inhabit indoors, along with its high capacity for transmitting the disease and impressive adaptability to changes in the environment. These biological and ecological traits establish A. gambiae as the primary malaria vector throughout much of tropical Africa, warranting its selection as the central focus of this review (12-15).

Biology and Life Cycle of *Anopheles gambiae*

Anopheles gambiae is an anthropophilic mosquito and, therefore, a primary malaria vector (3). The mosquito undergoes four successive life stages in its life cycle, including egg, larva, pupa, and adult. Initially, all stages of the mosquito feed on plant nectar, but adult females feed on blood to acquire the nutrients needed for the development of eggs (17). Approximately two days

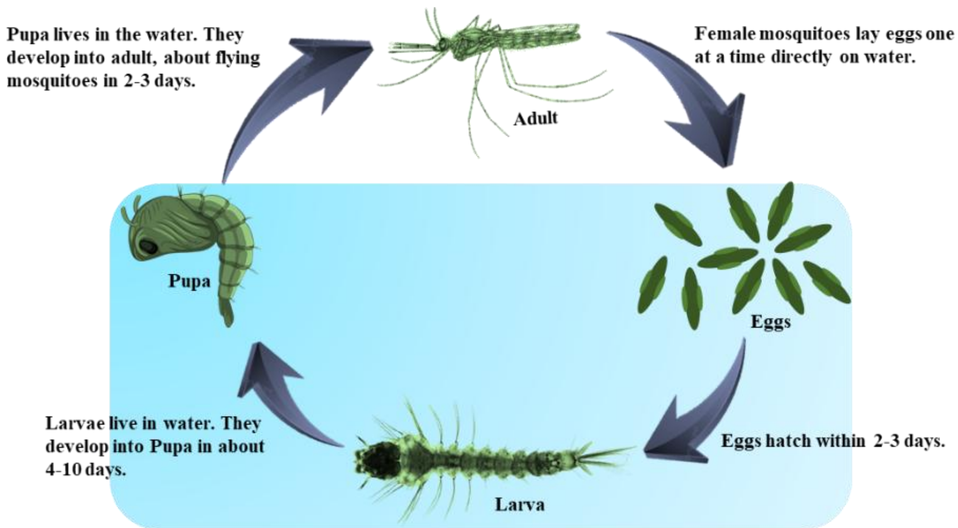

Figure 1: The complete developmental stages of A. gambiae from egg to adult are shown in Figure 1, highlighting the mosquito's adaptation to aquatic and terrestrial environments.

After a blood meal, females find suitable locations to lay their eggs overnight (18). The females lay their eggs on the surface of different types of aquatic habitats, including hoof prints, sunlit shallow pools, and swamps (15, 19). The egg-laying process takes around 1.48 ± 0.3 days, with a hatching success rate of 63.18 ± 23.94%. The larval stage shows different durations for each instar. The first instar (L1) lasts about 1.55 ± 0.21 days, while the fourth instar (L4) can stretch to 2.84 ± 0.71 days. The pupal stage spans 1.53 ± 0.36 days. *A. gambiae*, on average, takes 11.04 ± 2.25 days to complete its development from egg to adult, with a survival rate of 84.14% (20). Developmental time can take longer than normal when done at lower temperatures, with a maximum of up to three weeks (15).

A. gambiae shows the most active nighttime behavior, peaking from midnight to 4:00 a.m. (21). The environment has an impact on larval growth, especially in savannah and woodland areas (22). Research from 1984 to 2000 shows that *A. gambiae's* life cycle can last fourteen to twenty days (23, 24). Seasons shape population patterns, with numbers rising in rainy periods and reaching their highest point mid-season before dropping as water levels even out (15). These environmental factors and behaviors turn *A. gambiae* into a resilient and adaptable malaria vector.

Behavioral Ecology of Adult *Anopheles gambiae*

Feeding Behavior

A. gambiae primarily feeds at night while preferring human blood sources, thus driving its substantial contribution to spreading malaria (3, 4). Females actively search for blood meals during night hours, typically from 10 pm to 6 am, when humans are predominantly indoors resting (21). This specific feeding period increases the chances of contact between humans and vectors, allowing mosquitoes to have a complete meal without much disruption, thus enabling the proper development of *Plasmodium* parasites (25). Females take about 2–3 milligrams of blood in a single feeding, which is enough for the development of eggs since each gonotrophic cycle results in the laying of about 100 eggs according to the size and quality of the blood meal (26, 27). Typically, the blood meal is completed in about 3–5 minutes, and egg-laying happens 48–72 hours post-feeding (28). Besides blood meals, both male and female *A. gambiae* also depend on plant sugars to maintain their metabolic functions throughout all life stages, whether they are resting indoors or outdoors. The reliance of African mosquitoes on sugar as a food source establishes an entry point for vector management through Attractive Toxic Sugar Baits (ATSBs), enabling researchers to reduce mosquito populations (25).

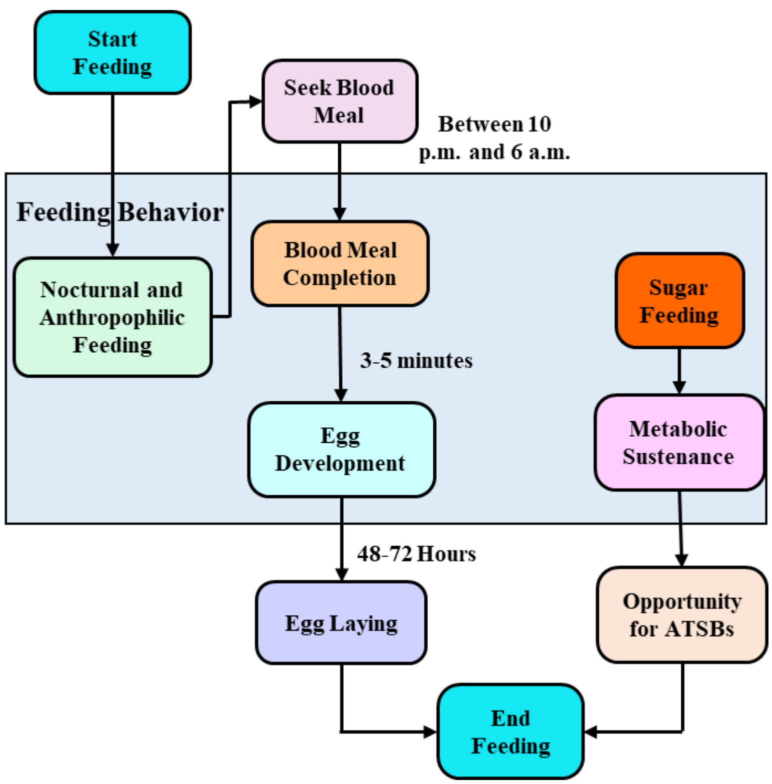

Figure 2: The nocturnal and anthropophilic feeding tendencies of A. gambiae are illustrated in Figure 2, emphasizing its peak biting activity between 22:00 and 04:00 h.

Reproductive Behavior

The reproductive behavior of *A. gambiae* consists of a specific mating ritual that includes male insects locating females through aerial swarming at dusk. This behavior increases the males' success in finding partners for mating. (29, 30). Most importantly, females mate once, storing sperm in their spermatheca to fertilize multiple groups of eggs throughout their lives. This way of mating makes reproduction more effective. It helps maintain large populations of mosquitoes, which can spread malaria (31, 32). Research indicates that *A. gambiae* swarms follow the hotspot model of lek formation, where larger swarms are associated with greater mating success. Individual males of these swarms have little to do with high per capita success. Notably, although the swarming behavior of *A. gambiae* has some similar characteristics to those seen in lekking species, they do not exhibit a strong preference for females. This indicates that their mating system might also include aspects of scramble competition (29).

Apart from the above, Environmental conditions like humidity and temperature are Important for successful mating. Swarming behavior is commonly seen in areas with consistently warm climates, enhancing male flight endurance and female receptivity (33). Additionally, biological factors such as male size and energy reserves are crucial for engaging in extended swarming and achieving effective copulation (34)These reproductive behaviors showcase the sophisticated adaptations of *A. gambiae*, promoting population robustness and continual malaria spread and thus informing targeted malaria control strategies.

Resting Behavior

After feeding, *A. gambiae* females predominantly exhibit resting behavior indoors, such as on walls, ceilings, or in dark and humid locations, which facilitates blood meal digestion and increases exposure to indoor insecticides (35-37). This behavior significantly enhances the effectiveness of interventions like insecticide-treated nets (ITNs) and indoor residual spraying (IRS) (38). Outdoor resting behavior has become more prevalent due to behavioral adaptations resulting from insecticide selection pressure, as reported by Owuor (2022). Research demonstrates that outdoor-resting behavior in *A. gambiae* populations is linked to genetic factors like the Vgsc-1014F mutation. The Vgsc-1014F mutation appears more often in outdoor-resting mosquitoes than in indoor-resting ones, which demonstrates a strong link between this genetic change and outdoor-resting behavior (39, 40). Although resistant mosquitoes live longer lives, they display decreased reproductive capabilities, which implies survival strategy trade-offs (41). The emergence of exophilic behavior and insecticide resistance highlights the critical need for monitoring mosquito resting patterns to develop effective control strategies and adapt interventions (42-44).

Table 1: Quantitative summary of key behavioral traits of adult *Anopheles gambiae*

Behavioral Trait	Quantitative Data	Environmental Influence	Citations
Feeding activity	Peak biting between 22:00–04:00 h	Increased by warm, humid conditions	(45)
Blood meal volume	2–3 mg per feeding	Larger meals increase egg production	(20)
Gonotrophic cycle	48–72 hours post-feeding	Shorter under high temperature	(46)
Resting duration	6–10 h post-feeding	Longer under high humidity	(12)
Average fecundity	80–120 eggs/female/cycle	Influenced by host availability	(47)

Influence of Environmental Factors on Vector Behavior

Climate Change

Climate change has a deep impact on how *A. gambiae*, a key malaria-carrying mosquito in Sub-Saharan Africa, acts and where it lives. As it gets warmer, these mosquitoes grow faster, which means they can reproduce more and spread malaria more (48). When it rains more, it creates both short-term and long-term places for mosquitoes to breed, which makes the malaria season last longer in many areas (49, 50). On the other hand, too much rain can have an impact on transmission by eliminating breeding areas and larvae (51). Relative humidity also plays a key role; long periods of low humidity in the dry season greatly reduce how long mosquitoes live, which limits the spread of malaria (52). Together, factors in the environment like temperature, rainfall, and humidity affect mosquito life cycles, where they can breed, and how well they can transmit pathogens (53). To predict malaria transmission patterns and create targeted, effective control plans, it's crucial to understand how these environmental elements interact.

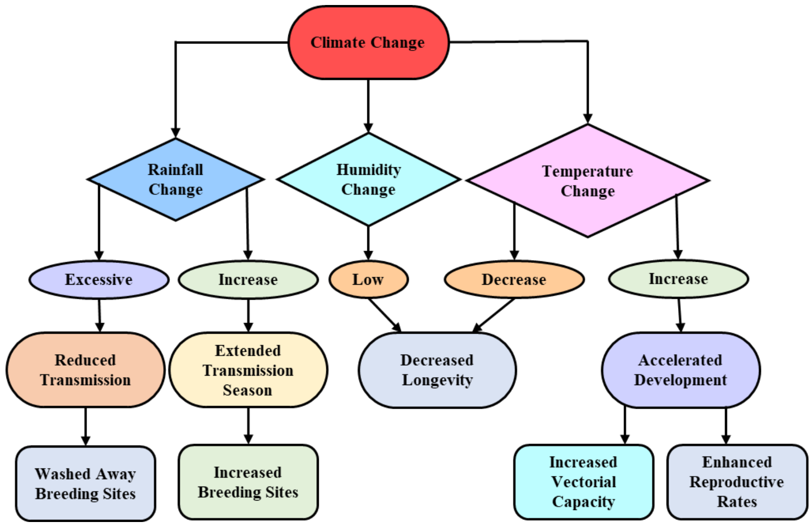

Figure 3: As depicted in Figure 3, temperature, humidity, and rainfall play critical roles in shaping the distribution and survival of A. gambiae.

Human Activities

The behavior and distribution of *A. gambiae*, an important malaria vector species, are deeply affected by human activities. Studies demonstrate that mosquitoes in urban areas prefer cattle as hosts over humans, in contrast to their behavior in rural habitats (54). Additionally, Mosquito populations have experienced altered enzymatic processes due to intensive insecticide application in agriculture, which may impact their survival rates and habitat distribution (55). Insecticide-treated nets (ITNs) and indoor residual spraying (IRS) programs effectively decreased mosquito populations yet simultaneously triggered insecticide resistance, which now complicates control measures (56). The emergence of altered mosquito biting behaviors, including increased outdoor feeding combined with changed nocturnal activity patterns, indicates a requirement for more advanced intervention methods (57). It's interesting that even with ITNs, some mosquitoes have learned to bite through these treated barriers and are still able to feed well (58). These findings show how human actions keep shaping mosquito behavior, highlighting the need for flexible and new ways to control these mosquitoes.

Table 2: Influence of climatic variables on *A. gambiae* development and transmission

Variable	Optimal Range	Effect on Vector	Transmission Impact	Citations
Temperature	25–30°C	Shortens larval period from 14 ⟶ 9 days	Accelerates parasite development	(59)
Relative Humidity	>60%	Increases adult survival from 6 ⟶ 14 days	Extends infective lifespan	(60)
Rainfall	50–150 mm/month	Expands breeding sites	Enhances vector density	(61)
Urbanization	—	Shifts biting to outdoor locations	Reduces IRS effectiveness	(62)

Malaria and Its Impact

Effects on Human Health

Malaria stands as a critical public health challenge for sub-Saharan Africa (63). Mosquitoes serve as vectors for this disease, which they transmit based on their population density levels and their specific biting behaviors, along with their lifespan (64). Mosquito bites induce hypersensitivity reactions and immune responses, which result in localized skin problems (65). Malaria symptoms begin with mild fever, sweating, headache, and vomiting, while progressing to severe conditions like seizures, coma, and kidney failure (66). Malaria during pregnancy dramatically increases the risks of maternal anemia, spontaneous miscarriage, premature delivery, growth restriction, low birth weight, stillbirth, congenital infection, and neonatal mortality (67). A hallmark of *Plasmodium falciparum* infection during pregnancy is parasite sequestration in the placenta, which contributes to severe adverse outcomes like early delivery, low birth weight, and increased neonatal mortality (68). Furthermore, vaccine allocation criteria should incorporate broader data and indicators to address malaria-related health risks and improve children's health and survival in affected regions (69). Malaria has significantly affected human health and survival alongside other health concerns in endemic regions.

Effects on Animal Health

Malaria is a concern for the health of animals in places where the *Plasmodium* species infects humans and animals. Some livestock, such as cattle, sheep, and goats, are hosts to some *Plasmodium* species that cause sicknesses, which decrease productivity and elevate death rates (70). Recent works have shown that some animals infected with *Plasmodium* manifest clinical fever, anemia, and weight loss, which is detrimental to livestock health and the economic value of livestock (71). *Plasmodium* is also harbored in goats and sheep, which hampers the control and eradication of malaria (70, 72). For example, Ethiopia has shown that the nearness of calves to human habitats is associated with increased mosquito breeding and a heightened risk of malaria, which underscores their part in the transmission cycle (73). Studies suggest that cattle can increase the population of mosquitoes and help propagate malaria (74, 75). Cattle, on the other hand, may provide some form of protection through lower human exposure to mosquitoes through zeoprophilaxis, while in some conditions, they can also contribute to mosquito breeding (76). In dealing with malaria in the worst-affected areas, it is important to take into account both human and animal health in a One Health strategy (77).

Economic and Social Burdens

Approximately 95% of all malaria cases occur in the African continent, with sub-Saharan Africa having the biggest malaria threat (78). The economic burden of malaria on households and individuals is substantial due to human morbidity and mortality; hence, this reduces labour productivity and output per worker. Malaria has a significant financial impact on families and people because of human sickness and mortality; as a result, labor productivity and production per worker are decreased. Therefore, malaria is a developmental and public health issue (78). Malaria and its direct health implications impact the socioeconomic development of affected areas. It significantly strains healthcare systems by using resources that may be used to address other urgent medical issues. Malaria treatment comes at a high cost, both in terms of direct medical bills and indirect costs like missed wages from illness (79). In Ethiopia, malaria places

14% of rural households at risk of catastrophic health expenditures, emphasizing its disproportionate impact on vulnerable populations (80). In Senegal, malaria-induced morbidity reduces annual GDP by an estimated US $108 million, underlining its long-term impact on national economic growth (81). On the other hand, because malaria affects household agricultural output, it lowers cereal yields by an average of 2.6% in the majority of SSA nations (82).

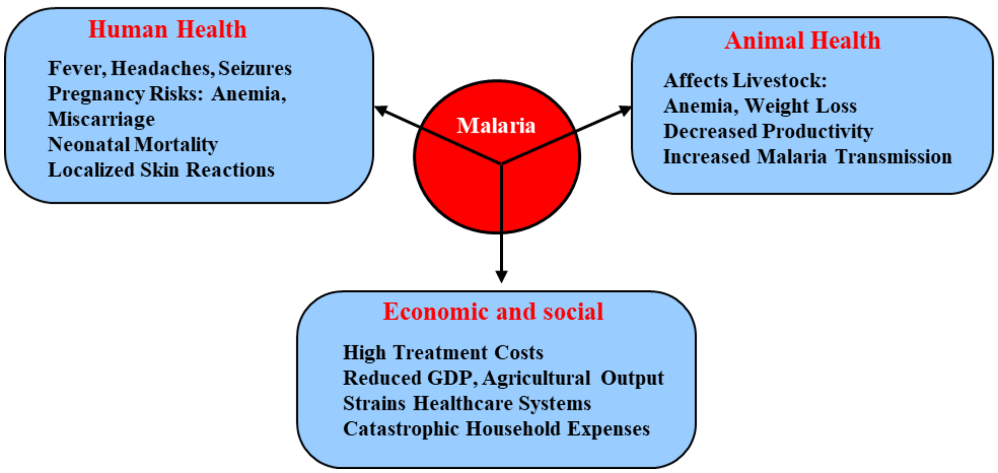

Figure 4: Figure 4 summarizes the multifaceted impact of malaria on health, productivity, and economic growth across Sub-Saharan Africa.

Malaria Transmission Dynamics

The transmission dynamics of malaria are deeply embedded within the behavioral ecology and environmental adaptability of *A. gambiae*, the primary vector for malaria transmission within Sub-Saharan Africa. This species has a notable role in *Plasmodium* parasite transmission, with some activity of the species varying due to ecological and seasonal changes. For example, Côte d'Ivoire records show that *A. gambiae* was responsible for 84.8% of malaria transmission cases in the region, with the highest biting and infection rates occurring in the rainy season. Yet, the vector endophily persisted throughout the year, even when rainfall levels were low (83). The mutations Kdr L1014F and Ace-1R G119S, along with other genetic elements, have been linked to resistance towards insecticides and have greatly impacted the adaptability and persistence of *A. gambiae* in regions with high vector management practices. It has been shown that these mutations are much more common in *A. gambiae* compared to other sibling species like *A. coluzzii*, which indicates that all of these species have varying degrees of tolerance towards insecticide exposure (84). As Kabupaten Banjarmasin in Burkina Faso studies have revealed, the 1014F-genotype, which is a known marker of insecticide resistance, is rampant in a variety of ecological settings. Even so, this study did not find any significant correlation between the 1014F-genotype and *A. gambiae* population *Plasmodium falciparum* infection, which implies that other factors are more important for averting malaria transmission (85).

Patterns of malaria have shown some alteration from what would be considered the norm due to environmental changes, even those resulting from anthropogenic activities. In Southwest Nigeria, more than 81% of the area was predicted to be *A. gambiae's* suitable range, while forecasts indicate drastic changes for the future climate scenarios (86). Moreover, *Plasmodium*-infected *A. gambiae* populations found in places like Cameroon persist despite the extensive use of long-lasting insecticidal nets (LLINS), indicating the need for additional vector control (87). Malaria transmission dynamics demand integrated strategies that address regional ecological and epidemiological differences while stressing the necessity for adaptive control measures to respond to changes in dominant vector species and their behaviors (1).

Innovative Control Strategies

Overview of Existing Malaria Control Strategies in Sub-Saharan Africa

Current malaria control efforts in Sub-Saharan Africa are guided by the World Health Organization's Global Technical Strategy for Malaria 2016–2030 (88), which emphasizes universal coverage of proven interventions, early detection, and sustained surveillance. The cornerstone approaches include the use of long-lasting insecticidal nets (LLINs) and indoor residual spraying (IRS), both targeting the nocturnal and indoor-resting behaviors of *A. gambiae* (89, 90). Larval source management and environmental modification have been adopted in specific ecological settings to reduce vector breeding habitats (91), while intermittent preventive treatment (IPTp) and prompt diagnosis and treatment with artemisinin-based combination therapy (ACT) remain central to reducing human infection rates (88). These strategies have significantly decreased malaria morbidity and mortality across the region (89). However, their long-term effectiveness is increasingly challenged by behavioral plasticity, outdoor biting tendencies, and insecticide resistance in *A. gambiae* populations (62, 92). Understanding these behavioral adaptations is therefore crucial for improving existing interventions and integrating novel technologies—such as gene drives, *Wolbachia* biocontrol, and next-generation vaccines—into adaptive, evidence-based malaria control programs (93, 94).

Emerging Genetic and Biological Approaches

Novel genetic and biological approaches will be significantly helpful in controlling malaria. Gene drives using the CRISPR system, specifically with Cas9 and Cas12a nucleases, have succeeded in *A. gambiae* population suppression by disrupting sex-determining genes in addition to introducing pathogen resistance traits. These measures represent greater precision and scale in targeting, but concern about the development of resistance and other ecological consequences must be considered (95, 96). At the same time, nanosilver mosquitoes have exceptional durability and efficacy against resistant populations of mosquitoes, thus offering a non-chemical alternative (97). Furthermore, the incorporation of *Wolbachia* bacteria, recognized for their ability to diminish mosquito lifespans and curtail disease transmission, has surfaced as an additional sustainable strategy (98, 99). Moreover, state-of-the-art computational technologies now play an essential role in the design of highly precise gRNAs, enhancing the efficiency of gene drives even among genetically diverse mosquito populations (100). By combining these new developments with conventional techniques like source reduction and insecticide rotation, researchers are forging a path toward integrated and adaptive strategies. Continuous field trials and ecological evaluations are crucial for ensuring the safety, efficacy, and scalability of these technologies in regions where malaria is endemic (93, 101).

Environmental Management Techniques

The core technique for combating malaria still mainly relies on environmental management, which aims to reduce places where mosquitoes reproduce and shift their habitats. Simple methods like vegetation clearance, draining stagnant water, and removing any unused containers have worked fairly well to lower mosquito populations in rural areas (102, 103). Furthermore, evidence also shows that the systematic modification of the ecosystem, in addition to the use of environmental systematic drainage, can be useful in controlling the number of mosquito larvae. Data from Ghana illustrates the effectiveness of education and community-based sanitation programs in reducing the availability of these habitats (104). More integrated strategies conducted with supportive larval source management and Ethiopian public health have successfully maintained lower mosquito populations over a period of three years, which supports the idea that more comprehensive approaches are needed in vector control (105). On the other hand, a housing modification by the use of wire mesh screens and improving the room ventilation is meant to reduce the risk of exposing people to indoor mosquitoes in high transmission zones (106). Nanosilver-based larvicides, for example, are highly effective as they persist for long periods and are potent against larvae in various aquatic ecosystems (97). These methods illustrate the critical role of environmental management in combining it with innovative community-led strategies for sustainable and effective malaria control.

Vaccine Development and New Pharmacological Interventions

Breakthroughs in vaccination and pharmacological treatments have refueled optimism for combating malaria, especially in areas of moderate to high transmission with *Plasmodium falciparum*. Among such immunological tools are the RTS, S/AS01, and R21/Matrix-M™ vaccines, which have shown an efficacy level of 80% in clinical studies (107, 108). Although its efficacy is approximately 40%, the effect of RTS S/AS01 is strongly amplified by control measures like the removal of stagnant water, the use of insecticide-treated mosquito nets, and indoor residual spraying (107). The antigens present in transmission-blocking vaccines (TBVs) specifically target the parasite residing within the mosquito host, offering the potential for community-wide protection by disrupting transmission cycles (109). In the same vein, monoclonal antibodies (mAbs), which provide instant passive immunity, are successfully used to manage malaria during seasonal exacerbations or in highly endemic regions (110). New pharmacological interventions, such as those based on nano silver technologies, are also emerging for their potential to interrupt the life cycle of the parasite at multiple points (97). All of these innovations highlight the importance of modern vaccination and other pharmacological interventions in augmenting the conventional methods of controlling malaria.

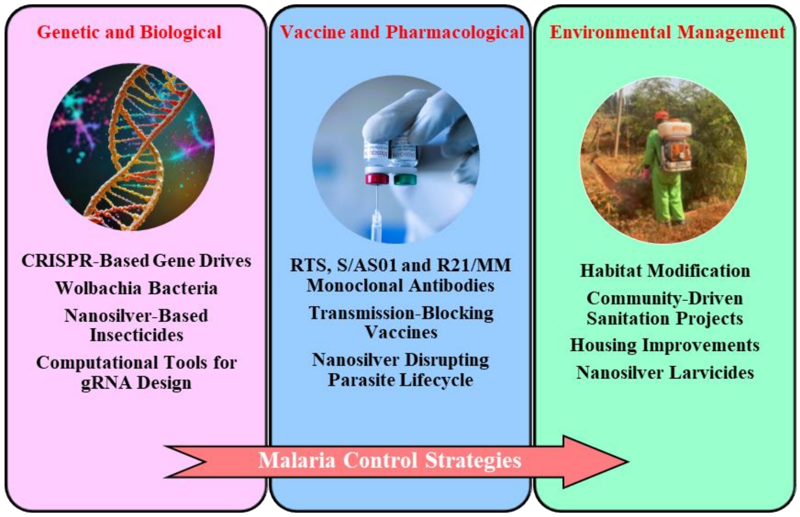

Figure 5: The integration of novel technologies, including gene drives, Wolbachia biocontrol, and malaria vaccines, is represented schematically in Figure 5.

Table 3: Effectiveness of selected malaria control interventions

Intervention	Efficacy / Reduction (%)	Study Region	Limitation	Citations
Long-lasting insecticidal nets (LLINs)	55–70% reduction in transmission	Tanzania, Kenya	Resistance to pyrethroids	(89)
Indoor residual spraying (IRS)	40–60% reduction in incidence	Zambia, Malawi	Costly, requires logistics	(111))
Gene drive (CRISPR-based)	>95% population suppression (lab)	UK, 2018	Ethical and ecological issues	(93)
Wolbachia infection	60–70% reduction in adult lifespan	Benin,2024	Limited field validation	(112)
R21/MM vaccine	75–80% efficacy within 6 months	Ghana, 2023	Declines over time	(94)

Future Research Directions

Despite progress in understanding *A. gambiae's* behavioral ecology and its part in spreading malaria, researchers still have a lot to uncover. Filling these knowledge gaps is key to creating new, effective ways to fight malaria. Here are some areas that future studies should look into:

Behavioral Adaptations and Resistance Dynamics

The increasing issue of insecticide resistance shown by the spread of Kdr L1014F and Ace-1R G119S mutations points out how important it is to grasp how *A. gambiae* mosquitoes change their behavior when faced with strong efforts to control them. To move forward, scientists should look at the genetic factors behind these changes and study their effects on the environment, the move towards resting and eating outdoors. By doing long-term genetic studies across different ecosystems, researchers can learn a lot about how resistance develops and how it affects the spread of malaria.

Integrating Climate and Socioeconomic Models

Environmental factors such as temperature, precipitation, and humidity have an impact on *A. gambiae* behavior, but adding these factors to predictive models that take into account social and economic factors has proven difficult. Scientists should aim to create all-encompassing frameworks that combine climate change forecasts with socioeconomic elements, like urban expansion and farming methods. This approach can enhance our capability to forecast changes in malaria transmission patterns and come up with targeted control strategies that adjust to these changes.

Advancing Genetic and Biological Control Tools

When CRISPR gene drives join with *Wolbachia* bacterial treatments, we obtain efficient modern population control methods to manipulate pathogens. The ecological repercussions, together with the long-term impacts and anti-resistance characteristics of these technologies, require thorough investigation. Multiple field experiments across various ecological zones will assess the practicality and security aspects, as well as the expandability and ethical and legal boundaries of implemented interventions. Anti-resistance elements need to be implemented because they present an essential requirement. The design of gRNA becomes more precise through computational research methods.

Community-Driven Environmental Management

Community engagement and awareness play a pivotal role in the effectiveness of environmental management strategies like habitat alteration and reducing larval breeding sites. Future studies should explore strategies to enhance community engagement, particularly in high-transmission areas. Assessing the socioeconomic barriers to participation and evaluating the effectiveness of integrated environmental and health interventions will be pivotal in optimizing these strategies.

Innovations in Vaccine and Pharmacological Research

While the RTS, S/AS01, and R21/MM vaccines represent significant milestones, their variable efficacy across populations highlights the need for next-generation malaria vaccines. Future research should aim to improve vaccine efficacy, particularly under real-world conditions in endemic regions. Developing monoclonal antibodies and nanosilver-based pharmacological solutions offers promising avenues for targeted malaria control. Investigations into their cost-effectiveness, accessibility, and long-term impact should be prioritized.

One Health Approaches in Malaria Control

The interconnectedness of human, animal, and environmental health offers a holistic approach to malaria control. Investigating the dual role of livestock as reservoirs and potential buffers for malaria transmission from a One Health perspective is crucial for future research. Assessing how livestock management practices influence mosquito density and *Plasmodium* prevalence could yield valuable insights for developing integrated control programs.

Urbanization and Malaria Transmission

A. gambiae has begun to evolve its ecological behavior alongside its host-seeking behavior because of rapid sub-Saharan African urbanization. Further investigations are necessary to study the complete impact of urban settings on vector biology and human contact with mosquitoes in compact living spaces. Recognizing specific urban threats requires immediate action to develop personalized intervention methods like waste management systems and enhanced urban living situations.

Strengthening Surveillance and Monitoring

A. gambiae behavior, population changes, and any modifications in resistance patterns necessitate extensive monitoring systems. Additional research should focus on more affordable, compact monitoring instruments, such as advanced geospatial maps of habitats or molecular markers that denote areas of resistance. Surveillance networks can be strengthened for more robust monitoring to enhance the effectiveness of vector control interventions and enable quick adjustments.

Future research should prioritize a multidisciplinary strategy that brings together progress in behavioral ecology, environmental management, genetic tools, and vaccine development. By addressing the identified information gaps and promoting collaboration among academics, politicians, and communities, the global effort to eliminate malaria can make significant strides. In Sub-Saharan Africa and other regions, the ever-changing nature of malaria transmission requires innovative and adaptable strategies to overcome emerging challenges and achieve sustainable control.

Conclusion

This review has underscored how feeding, reproductive, and resting behaviors, genetic resistance, and environmental influences such as urbanization and climate change sustain high transmission rates despite ongoing control measures. Furthermore, the significant health burden of malaria, including maternal mortality, neonatal complications, and its adverse impact on livestock, highlights the interconnectedness of human, animal, and environmental health. While current interventions, such as insecticide-treated nets and indoor residual spraying, have shown success, the evolution of insecticide resistance and shifting mosquito behaviors necessitate innovative and integrative approaches for sustainable vector control.

Emerging genetic tools, biological interventions like *Wolbachia*, next-generation vaccines, and community-driven environmental management provide promising avenues for reducing malaria transmission. However, these approaches require comprehensive field trials to evaluate their scalability, ecological safety, and socio-economic feasibility across diverse settings. Moving forward, multidisciplinary research integrating behavioral, ecological, and socio-economic data is crucial for designing adaptive and region-specific malaria control strategies. Strengthening surveillance systems, fostering community engagement, and adopting One Health frameworks will be pivotal in overcoming existing challenges. With coordinated efforts and sustained innovation, achieving the goal of malaria elimination in Sub-Saharan Africa is an attainable and impactful target.

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