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Mini Review

The Silent Strategist: *Anopheles* Mosquito as a Super-smart Vector

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Abstract

The *Anopheles* mosquito, the primary vector of malaria, poses a major global public health challenge in tropical and subtropical regions. They transmit *Plasmodium* through the bite of infected female *Anopheles* mosquitoes. Other than malaria, the vector is also an important transmitter of other infections such as lymphatic filariasis and O' Nyon Nyong. Their remarkable taxonomic diversity, adaptability, ecological plasticity, and behavioural heterogeneity, combined with expanding geographical ranges under climate and land use change, make them central drivers of the global burden of Malaria. Interactions among *Anopheles*, *Plasmodium* parasites, filarial worms, and the mosquito microbiota are highlighted to illustrate how parasite-vector co-evolution and symbionts influence vector competence and transmission dynamics. Understanding the mosquito-parasite relationship and transmission dynamics is essential for developing effective vector control strategies and reducing the global malaria burden.

Introduction

While many consider large predators like lions or sharks to be the world's most dangerous creatures, that title should arguably belong to a creature weighing less than 5 milligrams: the *Anopheles* mosquito. This genus of mosquito is the primary biological vehicle or vector for some of the most devastating diseases in the history of mankind, most notably malaria. *Anopheles*, *Culex*, and *Aedes* are the 3 most important mosquito genera causing diseases. Female *Anopheles* mosquitoes suck the blood of humans, non-human primates, and mammals and spread infections like Malaria. The British Army surgeon Ronald Ross discovered the development and life cycle of the malaria parasite (*Plasmodium* spp.) in the midgut of the *Anopheles* mosquito in 1897.

Comprising over 460 species, of which approximately 100 are able to transmit human malaria and 30–40 are of major public health importance, the *Anopheles* mosquito is quite adept at adaptation and transmission. Understanding its biology, life cycle, and the mechanisms by which it spreads disease is therefore critical to channelize global public health efforts. *Anopheles* mosquitoes are ubiquitous in most regions of the world except Antarctica, with distinct faunal assemblages seen across Afrotropical, Oriental, Australasian, and Neotropical zones of the world. Species composition, seasonality, and abundance of the mosquito vector are shaped by climate, land use, hydrology, and human settlement patterns of the region. This results in highly focal vector distributions and disease risks.

Anatomy and biology of the vector

The *Anopheles* mosquito is distinguished from other common mosquitoes (like *Aedes* or *Culex*) by several unique physical and behavioral traits.

1. **Resting position:** Perhaps the most prominent and recognizable feature of this mosquito is its resting posture. Unlike most mosquitoes that sit parallel to a surface, an adult *Anopheles* rests at a 45 ◦angle to the surface or substrate, with its abdomen pointing upwards. This distinguishes it from *Culex* and *Aedes*, which rest parallel to the substrate.

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2. **Palpi and proboscis:** Their maxillary palpi (sensory organs near the mouth) are as long as the proboscis, giving their "nose" a thickened appearance.

3. **The wings are mottled brown.**

4. **Nocturnal feeding:** Most *Anopheles* species are "crepuscular" or nocturnal biters, meaning they are most active and likely to bite between dusk and dawn.

The female of the species is the sole vector of disease. While both males and females feed on plant nectar for energy, the female requires a blood meal to obtain the protein and iron necessary for egg laying and the oestrous cycle. It is during this quest for blood that the cycle of disease transmission begins.

The life cycle of *Anopheles*

Anopheles mosquitoes undergo complete metamorphosis, through four distinct stages -egg, larvae and pupae followed by terrestrial adults. The first three stages are aquatic, rendering water management a cornerstone of vector control. Although ecological preferences may vary substantially among species, females usually oviposit directly on water, shallow and relatively clean bodies, in the case of many primary vectors.

The life of an *Anopheles* mosquito can be divided into four distinct stages: Egg, Larva, Pupa, and Adult. The first three stages are entirely aquatic, making water management a cornerstone of vector control.

Eggs: A female *Anopheles* mosquito lays 50–200 eggs directly on the water surface. *Anopheles* eggs are unique because they are laid singly and possess "floats" on either side to keep them buoyant and floating on the water. They are not resistant to drying and typically hatch within 2–3 days in tropical climates. Eggs are usually laid singly and possess "airfloats" on either side, which keep them buoyant.

Larvae: Once hatched, the larvae live just below the water surface. *Anopheles* larvae lack a respiratory siphon and lie parallel to the water surface to breathe through spiracles on their abdomen. Larvae feed on microorganisms and other organic matter, including bacterial biofilms on the water surface, which supply essential nutrients to them. Larvae have four instar stages.

Pupae: After four "instars" (or growth stages), the larva transforms into a comma-shaped pupa. This is a non-feeding stage where the mosquito undergoes metamorphosis.

Figure 1 and Table 1, appended below, highlights the larvae of *Anopheles* spp.

The malaria cycle

The relationship between the mosquito and the parasite is a complex biological phenomenon.

Ingestion: When a mosquito bites a person already infected with malaria, it sucks up blood containing male and female gametocytes (reproductive cells of the parasite).

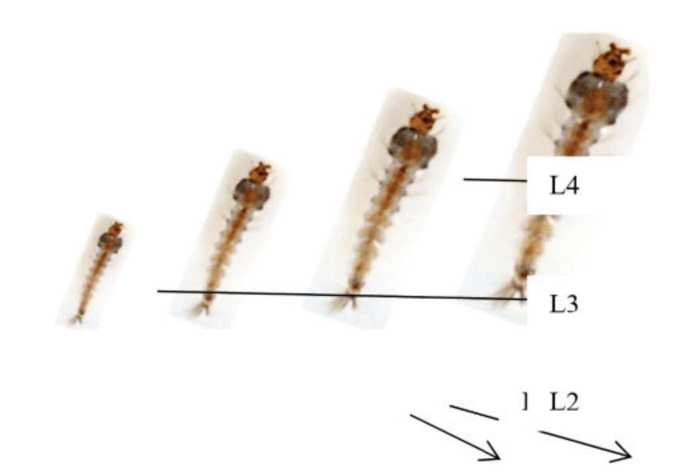

Figure 1: Larvae of *Anopheles* spp. (picture courtesy: Google images and Dr. Sweta Bhan).

Table 1: Developmental stages of *Anopheles* spp.

Life stage	Habitat	Morphological and biological features	Duration (tropical conditions)
Egg	Aquatic (water surface)	Eggs are laid singly on the water surface; boat-shaped with lateral floats that maintain buoyancy; highly sensitive to desiccation	2–3 days
Larva	Aquatic	Larvae pass through four instars; lack a respiratory siphon; remain parallel to the water surface, and respire through abdominal spiracles	5–7 days
Pupa	Aquatic	Comma-shaped, mobile, non-feeding stage; site of metamorphosis from larva to adult	1–2 days
Adult	Terrestrial	Slender-bodied mosquito; females possess long palps equal in length to the proboscis and are responsible for blood feeding and disease transmission	1–2 weeks or longer under favourable conditions

Development: Inside the mosquito's midgut at 22 °C - 25 °C, these gametocytes form gametes, which then fuse to form an ookinete, which burrows into the gut wall to form an oocyst. Within the oocyst, sprockets and then thousands of active sporozoites are produced. The life cycle of the malaria parasite in the midgut of the female *Anopheles* mosquito was discovered by the British army surgeon Ronald Ross in 1899.

Migration: The oocyst eventually bursts, and the sporozoites migrate through the mosquito's body to its salivary glands.

Inoculation: When the mosquito bites its next victim, it injects saliva containing an anticoagulant to keep the blood flowing. Along with that saliva, it unwittingly pushes the *Plasmodium* sporozoites into the human bloodstream. These sporozoites then migrate to the liver and transform into hepatic trophozoites. Then they enter the bloodstream after getting converted into merozoites. Merozoites enlarge and later form ring stages or trophozoites and then into male and female gametocytes, which are again taken up by mosquitoes after a bite or blood meal and develop as before in the mosquito midgut (Table 2).

Beyond malaria: Other diseases

While malaria is the most famous disease associated with this vector, *Anopheles* mosquitoes are also capable of

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Table 2: Important *Anopheles* species, their habitat and vector.

Species	Habitat	Disease transmitted
stephensii	Overhead tanks, desert coolers, and wells	Vivax and Falciparum malaria
sundaicus	Coastal areas	Vivax and Falciparum malaria
fluvialis	Flowing water of streams and rivulets	Vivax and Falciparum malaria
gambiae	Water in rural areas	Vivax and Falciparum malaria
dirus	Brackish, marshy water and water of the foothills	Vivax and Falciparum malaria
balabacensis	Jungles of Borneo and Sarawak, Indonesia, and adjoining areas	*Plasmodium knowledge* malaria
barbirostris	Freshwater and brackish aquatic environments	Uncommon vector of Malaria (non- vector)

transmitting other serious pathogens, which can be listed as follows:

(a) **Lymphatic Filariasis (Elephantiasis):** In certain regions, especially in Africa, *Anopheles* species transmit the parasitic nematode worms (*Wuchereria bancrofti*) that cause this disfiguring disease.

(b) **O'nyong-nyong virus:** O'nyong Nyong is a viral fever characterized by joint pain and rash, transmitted primarily by *Anopheles gambiae* and *Anopheles funestus*. The only clinical difference with Chikungunya is the absence of cervical lymphadenitis. The Acholi people of northwestern Uganda termed the disease 'o'nyong-nyong, literally translating into 'very painful weakening of joints'. This disease was first reported in Uganda, Africa, in the 1950s.

(c) **Heartworm:** They can also transmit *Dirofilaria immitis*, a nematode parasite primarily affecting dogs and cats.

The image below shows the life cycle of *Anopheles* spp (Figure 2).

Figure 3 below illustrates a representative image and the typical resting posture of *Anopheles* spp.

Public health impact

The impact of the *Anopheles* vector on human history, public health, and modern economics is simply staggering. According to the World Health Organization (WHO), there were an estimated 249 million cases of malaria in 2022, resulting in over 608,000 deaths. The majority of these fatalities are seen in sub-Saharan Africa, and tragically, children under the age of five are the most vulnerable.

Beyond the loss of life, the high burden of malaria also stunts economic growth significantly. It leads to billions of dollars in terms of lost productivity and also imposes an immense burden on the healthcare systems of developing nations. However, in India, now Malaria control has been successfully implemented to a large extent, and cases and other parameters like Slide positivity rate have declined significantly over the years.

Vector control: The battle against the bite

Since there is currently no 100% effective vaccine for malaria (though recent breakthroughs like the RTS.S/AS01 and R21/Matrix-M vaccine are promising), the primary way to stop the disease is to control the vector.

Strategies targeting *Anopheles* mosquitoes aim to reduce vector density, decrease mosquito longevity, limit human–vector contact, and interrupt parasite development within the mosquito [1]. Over the past two decades, vector control interventions have been responsible for the majority of the reduction in global malaria incidence and mortality [2].

Long-Lasting Insecticidal Nets (LLINs) are the most widely deployed malaria control tool and provide both a physical barrier and a chemical effect through contact insecticides [3]. Large-scale trials and programmatic evaluations have consistently demonstrated that high LLIN coverage significantly reduces malaria morbidity and mortality, particularly among children under five years of age and pregnant women [4]. However, the effectiveness of LLINs is increasingly compromised by declining insecticidal efficacy and inconsistent usage patterns [5].

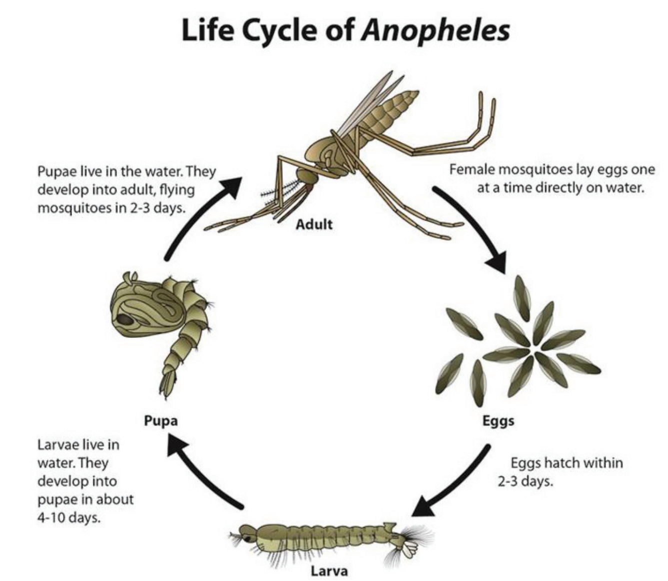

Figure 2: Image representing the life Cycle of *Anopheles* spp. Picture courtesy: www.animalia-life.club.

Figure 3: Resting stance of *Anopheles* spp. with abdomen pointing upward at 45⁰ angle (source: Google images).

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Indoor Residual Spraying (IRS) involves the application of residual insecticides on interior walls and surfaces where *Anopheles* mosquitoes commonly rest after blood feeding [6]. IRS has been shown to reduce vector survival and malaria transmission when implemented with high coverage and appropriate insecticide selection [7]. Its effectiveness is strongly dependent on local vector resting behaviour and susceptibility to the insecticides used [8].

Larval Source Management (LSM): This is very important, including environmental modification, habitat manipulation, and larval killing, can provide additional benefits in specific settings where mosquito breeding sites are limited, fixed, and identifiable. While LSM has proven effective in certain urban and peri-urban environments, its operational feasibility is limited in rural, forested, and flood-prone areas with extensive and transient breeding habitats [9,10].

Remote sensing and GIS (Geographic Information System) mapping may also help in gauging high-risk areas prone to infestation by *Anopheles* mosquitoes, which will help in better vector control.

Repellents: The use of long sleeved light coloured clothings can actively repel mosquitoes [11]. Usage of DEET or N-N Diethyl Toluamide can also be tried as a repellent. Originally developed in 1944 by the US Department of Agriculture, DEET interferes with the signals emanating from human skin that attract mosquitoes.

Disease control: The battle against the bite

A multi-pronged strategy can be applied for vector control. They are delineated as follows:

(a) **Vaccination:** Till now, there is no 100% effective vaccine for malaria disease, although recent breakthroughs like the R21/Matrix-M vaccine are promising, as seen in children below 5 years in endemic areas of Africa.

(b) **Vector control:** The only primary and surest way to stop the disease is by means of vector control. Use of insecticides of chemical or herbal origin (like Permethrin) assumes importance here. Biological vector control measures in water collection sites, like the use of *Bacillus thuringiensis* and larvivorous fish like *Guppy* spp. and *Gambusia affinis*, are also very important. The aerobic spore-bearing Gram-positive bacterium *B. thuringiensis* creates pores in the peritoneal lining of mosquito larvae and thus kills them.

(c) **MDA:** In countries where *Anopheles* vectors co- transmit malaria and lymphatic filariasis diseases, linking vector control with mass drug administration (MDA) can accelerate elimination of both diseases. Ivermectin can be used for this purpose successfully.

(d) **Insecticidal nets and Indoor residual spray:** These vector control strategies (like LLINs and IRS) can substantially reduce human-vector contact, leading to major declines in malaria burden since the early 2000s. Core malaria vector control strategies such as long-lasting insecticidal nets (LLINs) and indoor residual spraying (IRS) are able to reduce biting rates, while MDA reduces the human reservoir infection, resulting in lowering the probability that mosquitoes acquire infections during blood feeding. Evidence also consistently demonstrates that improving housing design reduces entry of mosquitoes and malaria prevalence [12]. Spatial repellents have also shown very promising results in field experiments, while evidence on plant-based repellents is limited and still emerging. These tools are most effective against endophagic and endophilic anopheline mosquitoes, which usually bite and rest indoors at night.

(e) **Larval Source Management (LSM):** This comprises environmental modification, habitat manipulation, larval killing, and biological control, which can be selectively deployed where aquatic habitats are relatively few, fixed, and searchable, like urban or peri-urban settings and certain irrigation schemes. *Anopheles* larvae are found most often inside water collected in rubber tyres and coolers. Spraying MLO or mosquito larvicidal oil will also help in the destruction of the mosquito larvae due to cutting off of Oxygen supply.

Conclusion

The female *Anopheles* mosquito is a very successful vector with many important species. It can transmit Malaria along with other diseases like lymphatic filariasis, O'nyong Nyong, and heartworm infection. Many strategies can be implemented to control the vector in the environment. Control of larvae and adults holds prime importance for the successful management of the *Anopheles* mosquito as a vector. More knowledge and awareness, hence, needs to be generated among the general public to effectively control Malaria and other infections spread by *Anopheles* spp.

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