

MOSQUITOES: TINY VECTORS, BIG THREATS - DECODING DISEASE THROUGH THE ONE HEALTH LENS

Mehedi Hasan¹ & Stanzin Dolkar²

¹PhD Scholar, Animal Biotechnology Division, National Dairy Research Institute, Karnal, India, 132001, ²Zoological Survey of India, M Block, New Alipore, Kolkata, West Bengal 700053, India

*Corresponding author email: 9hasanmehedi@gmail.com

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Abstract

Mosquitoes are much more than bothersome pests- they are active biological carriers that link humans, animals and the ecosystem, positioning them at the heart of the One Health strategy for disease prevention. With the increasing global impact of diseases transmitted by mosquitoes due to climate change, urban growth and ecological disruptions, traditional surveillance techniques are inadequate by themselves. This article examines how progress in veterinary biotechnology, especially DNA- and RNA-reliant methods like DNA barcoding, environmental DNA (eDNA), RT-qPCR, metagenomics and metatranscriptomics, is transforming mosquito monitoring through swift species identification, prompt pathogen detection and detailed observation of vector-related microbial communities. It also emphasizes the growing importance of artificial intelligence, whole-genome sequencing, microbiome studies and gene -editing technologies in forecasting disease outbreaks and enhancing integrated surveillance systems. Considering mosquitoes as biological sentinels instead just disease carriers, the article highlights the significance of molecular surveillance within the One Health approach for safeguarding human and animal health while maintaining ecosystem resilience in a more interconnected world.

Introduction

Despite their small size, mosquitoes continue to be one of the most harmful creatures impacting human health globally. These apparently minor insects are accountable for spreading various diseases that still place a significant strain on global health. The World Health Organization (WHO) reports that diseases spread by mosquitoes result in over 700,000 fatalities annually, with malaria accounting for almost 597,000 deaths in 2023, mainly affecting children under five in sub-Saharan Africa. Aside from malaria, mosquitoes act as carriers for numerous significant viral and parasitic illnesses, such as dengue, chikungunya, Zika, yellow fever, Japanese encephalitis, Rift Valley fever and West Nile fever, impacting hundreds of millions of individuals each year. Over the past few decades, elements like climate change, swift urban growth, higher global travel and changes in land use have led to the growth of mosquito populations and their spatial spread. Consequently, diseases transmitted by mosquitoes are progressively acknowledged as a significant threat to worldwide public health and an urgent issue within the One

Health paradigm, which highlights the interrelated health of people, animals and the ecosystem.

Mosquitoes: The Bridge between Humans, Animals and Environment

The One Health idea is grounded in a straightforward but strong notion: the well-being of humans, animal and environment is intricately linked. Mosquitoes illustrate this connection more distinctly than nearly any other disease carrier. Despite over 3,600 mosquito species being recognised globally, only a limited number are responsible for spreading pathogens that are significant to medical and veterinary fields. Species from the genera *Aedes*, *Anopheles* and *Culex* are crucial in transmitting illness to wildlife, livestock, pets and humans. Due to their consumption of various hosts throughout their lives, mosquitoes serve as natural conduits, aiding in their role in the transfer of pathogens between species and ecosystems.

Human actions and changes in environment have deepened this relationship.

Swift urban development, forest clearing, farming expansion, loss of biodiversity, irrigation initiatives and climate change have transformed mosquito breeding environments and population patterns, frequently establishing conducive conditions for disease spread. These ecological disruptions heighten the chances of interactions among wildlife, domestic animals and human communities, consequently elevating the risk of zoonotic disease emergence and pathogen transmission. As a result, efficient mosquito surveillance must expand beyond just tracking human disease. An all-encompassing One Health approach necessitates coordinated monitoring that includes human communities, livestock, wildlife and ecological systems, facilitating earlier identification of disease risks and improving the prevention of future epidemics.

DNA Technologies: Reading the Mosquito's Genetic Fingerprint

Modern molecular biology has transformed mosquitos into valuable sources of epidemiological information. Each mosquitoes contain remnants of DNA-not just its own genetic material but also DNA from the animal or human it has recently fed on and from microorganisms living in its digestive system. Using DNA barcoding of the mitochondrial cytochrome c oxidase I (COI) gene, researchers can swiftly differentiate morphologically alike mosquito species, including cryptic ones that vary in vector capacity. Environmental DNA (eDNA) methods now allow researchers to identify mosquito larvae in water samples prior to the emergence of adult mosquitoes, offering a proactive solution for vector management.

Recent developments in metagenomic next-generation sequencing (mNGS) enable the concurrent identification of mosquito species, blood-meal hosts, bacterial symbionts, parasites and DNA viruses from one mosquito sample. Research indicates that blood-meal DNA analysis can accurately identify livestock, birds, rodents, wildlife and human hosts, aiding in the reconstruction of transmission networks and prediction of zoonotic disease hotspots. This DNA-driven surveillance is increasingly essential for One Health monitoring systems.

RNA-Based Surveillance: Detecting Active Viral Threats

RNA offers up-to-date proof of present infections, whereas DNA discloses past

information. Reverse transcription quantitative PCR (RT-qPCR) and RNA sequencing are crucial for molecular surveillance because almost all medically significant mosquito-borne viruses, such as dengue, Zika, chikungunya, West Nile, Japanese encephalitis and Rift Valley fever, have RNA genomes.

The discovery of arboviruses has been transformed by RNA sequencing, which allows researchers to find viruses that were previously unknown without knowing their genetic sequences. Thousands of RNA viruses linked to mosquitoes have recently have been identified by researchers; ten years ago, many of these viruses were absolutely unknown. This expanding "mosquito virome" indicates a massive reservoir of viral diversity from which future emerging diseases may originate, even though the majority do not infect people. Continuous RNA surveillance therefore functions as an early-warning system capable of detecting viral evolution before widespread outbreaks occur.

Metagenomics: Seeing Complete Biological Picture

A mosquito is more than just an insect; it is a little ecosystem that is home to a little ecosystem that is home to a variety of bacteria, fungus, viruses and protozoa. These bacteria, together referred to as the mosquito microbiome, have a significant impact on mosquito development, immunology, lifespan and pathogen transmission. The bacterium *Wolbachia*, which naturally prevents dengue, Zika, chikungunya and yellow fever viruses from replicating inside *Aedes aegypti*, is one of the most amazing discoveries in vector biology. Field tests carried out in a number of nations have shown significant drops in dengue incidence after *Wolbachia*-infected mosquitoes were released, demonstrating how modifying the mosquito microbiome might lower disease transmission without only using insecticides.

Genomics and Artificial Intelligence: Predicting the Next Outbreak

The combination of genomics with artificial intelligence (AI), satellite remote sensing and geographic information system (GIS) is transforming mosquito surveillance. Whole-genome sequencing allows scientists to track insecticide-resistance genes, population dynamics and evolutionary developments in mosquito vectors. At the same time, AI algorithms integrate genomic information with climate factors,

including rainfall, temperature, humidity, vegetation indices and human movement to predict disease outbreaks weeks prior to the emergence of clinical cases.

Nations are progressively implementing these digital monitoring systems to focus on vector-control measures. Public health agencies can now foresee disease hotspots and implement preventive measures proactively, transitioning from a reactive approach to a predictive one instead of responding after outbreaks happen.

Gene Editing: Reprogramming the Mosquito

A highly fascinating advancement in mosquito research is the use of CRISPR-Cas9 for genome editing. Researchers have modified mosquitoes to carry gene drives that can quickly disseminate preferred genetic traits within natural populations. These characteristics may either reduce mosquito numbers or make mosquitoes unable to spread malaria parasites or arboviruses.

Gene-drive technology, while still undergoing through ecological and ethical assessment, stands out as one of the most

promising advanced tools for controlling vectors. When paired with Wolbachia-based strategies and traditional vector control, genetic innovations could significantly lower the burden of mosquito-transmitted diseases in the years ahead.

Future Outlook

The future of mosquito monitoring involves combining DNA sequencing, RNA sequencing, environmental DNA, metagenomics, AI-driven analytics, remote sensing, climate modelling and One Health surveillance into a cohesive system. Instead of wasting of patients to show up in hospitals, researchers are increasingly promoting proactive monitoring of mosquitoes. Each mosquito rapped serves as a biological sensor that can uncover circulating pathogens, host preferences, environmental changes and potential disease threats. With the advancement of genomic technologies that are quicker, less expensive and more portable, mosquitoes could emerge as one of humanity's key allies in stopping the next epidemic before it starts.

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