· Review ·

# Research progress on mosquito repellents and prevention of mosquito-borne diseases

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## Abstract

Mosquito-borne diseases remain a critical focus in global public health, with conditions such as malaria, dengue fever, and chikungunya fever causing millions of infections and deaths worldwide annually, posing a persistent threat to human health. Nearly half of the global population is at risk of mosquito-borne infections. Concurrently, environmental factors including climate change and accelerated urbanization are expanding the geographic distribution of these diseases, further complicating prevention and control efforts. This study systematically examines two core strategies: insect repellent development and vector control. It details the current applications of chemical repellents, natural plant-based repellents, and spatial repellents, while systematically analyzing implementation priorities for integrated vector control, comprehensive vector management, disease diagnosis and vaccine development, and public health education. The research identifies key challenges in vector control, including pesticide resistance, climate change, and emerging pathogens. Based on existing findings, it outlines future directions for innovative repellent development, biological control technologies, epidemic monitoring systems, and interdisciplinary collaboration. The study concludes that effective vector control requires a dynamic, multi-strategy integrated system adaptable to evolving mosquito behaviors, environmental conditions, and pathogen characteristics.

**Keywords:** mosquito-borne diseases, insect repellents, vector control, public health, insecticide resistance, integrated pest management

Mosquito control and prevention of mosquito-borne diseases are critical components of global public health, as vector-borne diseases such as malaria, dengue fever, chikungunya, yellow fever, and Zika virus infection cause millions of cases and deaths annually [1–3]. The continuous rise in these diseases has progressively become a major threat to global public health [2, 4]. Effective management of mosquito populations and prevention of bites require a combination of multiple strategies, which is of paramount importance [4, 5].

## Global overview and impact of Mosquito-borne diseases

Mosquitoes, as vectors of numerous pathogens, are among the most lethal animals on Earth [3, 6]. They

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rank among the most dangerous organisms due to their capacity to transmit various pathogenic microorganisms. These insects transmit diseases including malaria, dengue fever, yellow fever, chikungunya, Zika virus, West Nile virus, and lymphatic filariasis [1, 2, 7, 8]. Approximately 4 billion people worldwide, accounting for about 50% of the global population, are at risk of infection from mosquito-borne diseases [5]. For instance, dengue fever is prevalent in over 100 countries, particularly in Africa, the Americas, Southeast Asia, and the Western Pacific region [9]. Mosquito-borne diseases cause approximately 700,000 to 1 million deaths annually, with malaria being the most lethal among them. According to the Global Burden of Disease Study 2021, malaria resulted in approximately 608,000 deaths worldwide in 2021, of which about 76% were children under 5 years of age. Although dengue fever has a relatively low case fatality rate, its epidemiological impact is substantial, with an estimated 100 to 400 million symptomatic cases annually. In 2023 alone, over 5 million cases were reported globally, leading to more than 3,000 deaths. Yellow fever can cause tens of thousands of annual deaths in unvaccinated regions. While Zika virus rarely causes direct fatalities, congenital Zika syndrome (e.g., microcephaly) has been reported in over 2,000 confirmed cases during the 2015-2017 Brazilian outbreak. The geographical spread of mosquito-borne diseases is expanding, closely linked to environmental factors such as climate change, urbanization, deforestation, and inadequate drainage systems [2, 6, 7]. For example, climate change can alter the geographic distribution of mosquitoes and the exogenous incubation period of pathogens within their bodies, thereby reshaping the global risk profile of mosquito-borne diseases [6].

## Mosquito repellent strategies

Mosquito repellent is one of the key methods of personal protection, which reduces the risk of infection by preventing mosquitoes from approaching or biting human hosts [10–12]. Repellents work by interfering with the host-seeking behavior of mosquitoes [10].

### *Chemical repellents*

Using high-efficiency chemical repellents is the key method to protect oneself.

*DEET*: DEET (N, N-diethyl-3-methylbenzamide) is considered the gold standard for mosquito repellents and has been used for decades [13]. However, the emergence of mosquito resistance to DEET has prompted the development of novel repellents [13].

*Picaridin and IR3535*: In addition to DEET, picaridin and IR3535 are also widely recommended synthetic repellents.

*Other synthetic repellents*: Recent studies have focused on developing novel silicone-based mosquito repellents to address the limitations of existing repellents and prolong protection duration [13]. For instance, one study synthesized and evaluated a series of novel silicone compounds as potential mosquito repellents, aiming to enhance protective efficacy [13].

*Sustained-release formulations*: To prolong the effective duration of repellents, researchers are developing sustained-release formulations, such as encapsulating repellents in microcapsules to achieve more prolonged protection [14, 15]. The use of poly(ε-caprolactone) microcapsules encapsulating citronella oil has been demonstrated for mosquito repellent efficacy [15].

### *Natural plant-based repellents*

With the increasing concern about the resistance to synthetic pesticides and the potential harm to the environment and human health, plant-based repellents

have attracted more and more attention [1, 16–21].

*Essential oils*: Essential oils such as lemongrass, eucalyptus, clove, and marigold have been evaluated for their mosquito repellent efficacy and can be applied to textiles to provide protection [22]. Lemongrass oil is a common natural plant product that has been used in repellent formulations [12].

*Plant Extracts*: Extracts from plants such as Azadirachta indica and Vitex negundo are used to prepare herbal mosquito repellents due to their repellent effects against vectors of various mosquito-borne diseases (e.g., dengue fever, malaria, Zika virus infection) [20, 21]. Studies have demonstrated that plant monomeric compounds exhibit significant potential as mosquito repellents in combating mosquito-borne diseases, as they generally possess superior biodegradability and are less prone to resistance development [19].

*Blended formulations*: Studies have demonstrated that the combination of β-caryophyllene oxide and vetiver oil exhibits synergistic repellent and stimulant effects against multiple mosquito species, including Aedes aegypti, Aedes albopictus, Aedes microcephalus, and Culex trituberculatus [23].

*Formulation*: Natural repellents can be formulated into various forms such as sprays, emulsions, roll-ons, and scents [12, 17, 18]. A study developed and evaluated a herbal roll-on mosquito repellent formulation aimed at providing safe and effective personal protection [18].

*Mosquito-repellent textiles*: The application of mosquito-repellent ingredients (including synthetic chemicals and natural extracts) to textiles can be used to produce mosquito nets, clothing, and uniforms, providing sustained protection for individuals [22, 24].

***Spatial repellents***

Spatial repellents repel mosquitoes by releasing volatile compounds into the environment [25]. Deltamethrin, a volatile pyrethroid insecticide, achieves both pest control and repelling effects through widespread application. Studies have demonstrated that low concentrations of deltamethrin can effectively repel Aedes aegypti by enhancing the response of olfactory receptors [25].

## Prevention and control strategies for Mosquito-borne diseases

The prevention and control of mosquito-borne diseases require a multifaceted and comprehensive approach, including vector control, disease surveillance, public education, and personal protection [26–28].

***Vector Control***

Vector control is a key strategy to reduce the transmission of mosquito-borne diseases, aiming to decrease mosquito population density or their ability to transmit pathogens [4, 26, 29].

*Environmental management and fecundity site removal*: The elimination of mosquito breeding sites is one of the most direct and effective methods for controlling mosquito populations [26, 30]. This involves measures such as removing standing water from tires, flower pots, and discarded containers [30]. Emerging technologies, such as drones or automated patrol vehicles, are being developed for the detection and removal of mosquito breeding sites [31].

*Chemical control:*

Larvicides: Used to kill mosquito larvae and can be applied in waterlogged areas [11, 30]. Mosquito control agents: including indoor residual spraying and ultra-low volume spraying, which can rapidly reduce the

density of adult mosquitoes [32]. Pesticide resistance: However, long-term use of synthetic insecticides has led to widespread resistance in mosquitoes, severely threatening the effectiveness of traditional vector control strategies [1, 3, 5, 29, 32–35]. For example, the increase in dengue fever cases in India is consistent with the rising trend of resistance to insecticides in Aedes aegypti [35].

*Biological control:*
Mosquito-eating fish: Capturing mosquito larvae through fish schools [36]. The Israeli subspecies of Bacillus thuringiensis is a bacterial insecticide specifically effective against mosquito larvae [36]. Wolbachia: By infecting mosquitoes, Wolbachia bacteria can inhibit viral replication within mosquitoes and affect mosquito reproduction, thereby reducing the transmission of mosquito-borne diseases [29].

As alternatives to chemical pesticides, entomopathogenic fungi such as Beauveria spp. and Metarhizium spp. are being investigated for mosquito control [33].

Sterile Insect Technique is a method that releases radiation-treated or genetically edited sterile male mosquitoes to mate with wild female mosquitoes, thereby reducing mosquito populations [3].

*Synthetic Biology and Gene Drive*: Gene drive technology utilizes gene-editing tools such as CRISPR to rapidly propagate specific genes (e.g., those causing sterility or reduced viral transmission capacity) within mosquito populations, thereby achieving suppression or modification of mosquito populations to block disease transmission [3].

*Surfactants*: Studies have demonstrated that surfactants can alter the flight capacity and physiological status of mosquitoes, potentially serving as a novel vector control strategy [37].

***Integrated Vector Management***

The Integrated Vector Management (IVM) strategy recommended by the World Health Organization emphasizes multisectoral collaboration and evidence-based decision-making, integrating environmental, biological, and chemical control methods to achieve effective control of mosquito-borne diseases [27]. IVM aims to optimize the combination of various interventions based on local conditions to achieve synergistic effects [27].

***Disease treatment and vaccines***

*Treatment methods*: Currently, there are no specific antiviral drugs or long-lasting vaccines widely used for the treatment of diseases such as dengue fever [9]. Studies have explored the potential of drugs such as loratadine in reducing the incidence of dengue hemorrhagic fever, as it can decrease endothelial dysfunction in vitro and reduce vascular leakage in mouse models [38].

*Vaccine development*: Although vaccines are available for diseases such as malaria and yellow fever, the development of effective vaccines for many mosquito-borne diseases, including dengue fever, remains challenging [19].

***Public health and education***

*Public awareness*: It is crucial to enhance public understanding of the risks of mosquito-borne diseases and personal protective measures [11, 27].

*Early diagnosis and surveillance*: Rapid and accurate diagnosis, along with an effective disease surveillance system, contributes to controlling the outbreak [24].

## Challenges and Future Directions

***Prevention and control of Mosquito-borne diseases face multiple challenges***:

*Pesticide resistance*: The development of insect resistance to multiple pesticides represents one of the most significant challenges in contemporary pest control [1, 3, 5, 29, 32–35].

*Climate change*: Global warming leads to the expansion of mosquito activity ranges, thereby increasing the likelihood of disease transmission [2, 6].

*Emerging pathogens*: The emergence of new mosquito-borne viruses (e.g., Zika virus) and mutations in existing viruses have increased the complexity of prevention and control efforts [2].

***Future research directions include***:

*Development of novel repellents and insecticides*: The objective is to identify environmentally safer alternatives that are less prone to resistance development and exhibit prolonged efficacy [12, 13, 19].

*Innovations in biological control methods*: Continued development and refinement of biological control technologies based on Wolbachia, gene drive, and insect pathogenic fungi [3, 33].

*Integrated monitoring and prediction*: Utilizing mathematical models and data analysis to predict disease outbreak risks and guide the deployment of interventions [4, 11, 29]. A study proposed a mathematical model for dengue transmission incorporating the use of mosquito repellents, and analyzed its stability and optimal control strategies [4].

*Multidisciplinary collaboration*: Strengthen cooperation in fields such as medicine, ecology, entomology, engineering, and social sciences to jointly address the challenges of mosquito-borne diseases [28].

The prevention of mosquito-borne diseases requires a continuously evolving, multi-strategy integrated approach to adapt to the ever-changing mosquito behaviors, environmental conditions, and pathogen characteristics [5].

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## Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dai Shi, Taotao Wei, Shengli Yue, Min Lin, Lei Zhou, and Jiakang Yu. The first draft of the manuscript was written by Dai Shi and all authors commented on previous versions of the manuscript. All authors read, revised and approved the final manuscript.

## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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